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John Ballato, Mike Bass, Martin Richardson, Bryce Samson

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14. ABSTRACT
This program focused on new materials and fiber designs towards the realization of 100+ kW class eye-safe fiber lasers based on the following guiding principles: large mode area, single mode, purity of polarization state, minimization of nonlinear effects, compatibility with all-fiber pumps, and high temperature buffer coatings. Over the duration of this program the most significant findings are discussed below in the following sections:
1. Gain guided index anti guided fiber lasers

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Report Title

Final Report on High Power Fiber Lasers; Grant W911NF0510517

ABSTRACT

This program focused on new materials and fiber designs towards the realization of 100+ kW class eye-safe fiber lasers based on the following guiding principles: large mode area, single mode, purity of polarization state, minimization of nonlinear effects, compatibility with all-fiber pumps, and high temperature buffer coatings. Over the duration of this program the most significant findings are discussed below in the following sections:

1. Gain guided index anti guided fiber lasers
2. High temperature fiber coatings
3. Tm doped fiber lasers
4. Tm doped Photonic Crystal Fiber (PCF) lasers

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

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Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. A. E. Siegman, Y. Chen, V. Sudesh, M. Richardson, M. Bass, and J. Ballato, “Large area, near single mode oscillation in gain guided, index anti-guided fibers,” Optical Society of America annual meeting October 2006.
2. G. Frith, J. Farroni, A. Carter, B.Samson, K. Tankala, “High efficiency 110W Monolithic FBG tuned 2 μm fiber laser,” CLEO Europe, Munich, (2007).
3. G. Frith, et al., “Monolithic fiber lasers and amplifiers for the eye-safe region,” SPIE LASE 2007, Fiber Lasers IV, San Jose, CA (2007).
4. B. Samson, J. Edgecumbe, D. Machewirth, K. Tankala, M. O’Connor, A. Carter and G. Frith, “High Efficiency, Monolithic LMA Fiber Lasers and Amplifiers Operating at 1 μm and 2 μm Wavelengths,” SPIE Defense & Security, Orlando, FL (2007).
5. A. Siegman, J. Ballato, Y. Chen, V. Sudesh, M. Richardson, and M. Bass, “Large Area, Near Single Mode Oscillation in Gain Guided, Index Anti-Guided Fibers,” OSA Annual Meeting, Rochester, NY, (2006).
6. Y. Chen, V. Sudesh, M. Richardson, M. Bass, J. Ballato, and A. Siegman, “Experimental Demonstration of Gain Guided Lasing in an Index Anti Guiding Fiber,” Advanced Solid State Photonics (ASSP), Vancouver, British Columbia, (2007).
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8. A. Siegman, “Gain-guided Optical Fibers,” Liekki Corporation, Lohja, Finland, April 2006. INVITED
9. A. Siegman, “High-Power (Kilowatt-Level?) Gain-Guided Fiber Lasers” seminar given at the Optoelectronics Research Centre, Tampere University of Technology, Tampere, Finland, April 2006. INVITED
10. A. Siegman, “Coupled Fiber Laser Structures” IEEE/LEOS Summer Topical Meeting on Fibers for Lasers, Amplifiers and Nonlinear Applications, Quebec, Canada, July 2006. INVITED
11. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Optics Research Center, University of Southampton, Southampton, UK, June 2007. INVITED
12. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Integrated Optical Micro Systems (IOMS) Group, Department of Electrical Engineering, University of Twente, Enschede, The Netherlands, June 2007. INVITED
13. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Institute for Optics, Information and Photonics, University of Erlangen-Nuremberg, Germany, June 2007. INVITED
14. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Department of Physics, University of Hamburg, Hamburg, Germany, June 2007. INVITED
15. A. E. Siegman, "Gain guided, index antiguided fiber lasers" (Invited Paper), OSA Annual Meeting: Frontiers in Optics, San Jose, California, September 2007. INVITED
16. McComb T., Sudesh V., Chen Y., Bass M., Richardson M., Ballato J., and Siegman A. E. “Single mode lasing in gain-guided index anti-guided diode end pumped fiber,” Paper no. CThL5, CLEO 2008
17. Kim H. Su, McComb T., Sudesh V., and Richardson M., “Numerical investigation of beam propagation inside an index antiguided fiber laser,” Paper no. JTuA80, CLEO 2008
18. McComb T., Sudesh V., and Richardson M, “Narrow linewidth volume Bragg grating stabilized thulium fiber laser,” Paper no. CFD3, CLEO 2008
19. M. Bass, Y. Chen, T. McComb, W. Hageman, V. Sudesh, M. C. Richardson, A. E. Siegman, and J. Ballato, “Gain Guided, Index Anti Guided Fiber Lasers,” 20th Annual Laser Physics Symposium, Trondheim, Norway, 30 June, 2008. PLENARY TALK
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21. T. McComb, R. Sims, M. Reichert, V. Sudesh, M. Richardson, M. Poutous, Z. Roth, and E. C. Johnson, “VBG and GMRF stabilized continuous wave, tunable (50 nm), narrow linewidth, thulium fiber laser,” Photonics West, San Jose, CA, January 2009.
22. V. Sudesh, T. McComb, R. Sims, L. Shah and M. Richardson, “High power, tunable, CW, narrow line thulium fiber laser for ranging applications,” Advanced Solid-State Photonics, Denver, CO, February 2009.
23. R. Sims, V. Sudesh, T. McComb, Y. Chen, M. Bass, M. Richardson, A. G. James, J. Ballato and A. E. Siegman, “Diode-pumped very large core, gain guided, index antiguided single mode fiber laser,” Advanced Solid-State Photonics, Denver, CO, February 2009.
24. T. Ehrenreich, V. Khitrov, G. Frith, J. Farroni, K. Farley, K. Tankala, A. Carter, S. Christensen, B. Samson, D. Machewirth, High Efficiency 20W Single Frequency PM Fiber Amplifier at 2037nm,” Advanced Solid-State Photonics, Denver, CO, February 2009.
25. G. Frith, T. McComb, B. Samson, W. Torruellas, M. Dennis, A. Carter, V. Khitrov and K. Tankala, Frequency Doubling of Tm-doped Fiber Lasers for Efficient 950nm Generation,” Advanced Solid-State Photonics, Denver, CO, February 2009.
26. S. Christensen, T. Ehrenreich, V. Khitrov, J. Edgecumbe, K. Tankala, A. Carter and B. Samson, “Developments in Monolithic High Efficiency Tm-doped Fiber Lasers/Amplifiers,” SPIE Defense and Security, Orlando, FL, April 2009.
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28. B. Samson, A. Carter, K. Tankala and G. Frith, “Developments in High Efficiency Tm-doped Fiber Lasers/Amplifiers”, CLEO Europe 2009, Tech Focus Session, INVITED.
29. V. Khitrov, T. Ehrenreich, K. Tankala, A. Carter, S. Christensen, B. Samson, “Latest results on power scaling monolithic high

efficiency 2um fiber lasers", SPIE Defense and Security Europe, Berlin, August 2009.

30. R.A. Sims, C.C.C. Willis, P. Kadwani, T.S. McComb, L. Shah, V. Sudesh, Z. Roth, M. Poutous, E.G. Johnson, M. Richardson, "Spectral beam combining of thulium fiber laser systems," presented at Photonics West LASE, San Francisco, CA, January 2010
31. T.S. McComb, L. Shah, R.A. Sims, V. Sudesh, M. Richardson, "High power tunable thulium fiber laser with volume Bragg grating spectral control," presented at Photonics West LASE, San Francisco, CA, January 2010
32. R.A. Sims, T. Dax, Z. Roth, T.S. McComb, L. Shah, V. Sudesh, M. Poutous, E. Johnson, M. Richardson, "Spectral narrowing and stabilization of thulium fiber lasers using guided-mode resonance filters," presented at Photonics West LASE, San Francisco, CA, January 2010
33. C.C.C. Willis, L. Shah, M. Baudelet, P. Kadwani, T.S. McComb, R.A. Sims, V. Sudesh, M. Richardson, "High-energy Q-switched Tm^{3+}-doped polarization maintaining silica fiber laser," presented at Photonics West LASE, San Francisco, CA, January 2010
34. T.S. McComb, L. Shah, R.A. Sims, C.C.C. Willis, P. Kadwani, V. Sudesh, M. Richardson, "Atmospheric propagation testing with a high power, tunable thulium fiber laser system," presented at Photonics West LASE, San Francisco, CA, January 2010
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37. T. S. McComb, P. Kadwani, R. A. Sims, L. Shah, C. C. Willis, G. Frith, V. Sudesh, B. Samson, and M. Richardson, "Amplification of Picosecond Pulses Generated in a Carbon Nanotube Modelocked Thulium Fiber Laser," presented at Advanced Solid State Phontonics (ASSP), San Diego, CA, February 2010
38. W. B. Hageman, Y. Chen, M. Bass, V. Sudesh, T. McComb, M. Richardson, and G. Kim, "Diode Side Pumping of a Gain Guided, Index Anti-Guided Large Mode Area Neodymium Fiber Laser," presented at Advanced Solid State Phontonics (ASSP), San Diego, CA, February 2010
39. R. A. Sims, C. C. Willis, P. Kadwani, T. S. McComb, L. Shah, V. Sudesh, Z. A. Roth, M. K. Poutous, E. G. Johnson, and M. Richardson, "Spectral Beam Combining of 2 µm Tm Fiber Laser Systems," presented at Advanced Solid State Phontonics (ASSP), San Diego, CA, February 2010
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41. T. S. McComb, R. A. Sims, C. C. Willis, P. Kadwani, L. Shah, and M. Richardson, "Atmospheric Transmission Testing Using a Portable, Tunable, High Power Thulium Fiber Laser System," presented at the Conference on Lasers and Electro-optics (CLEO), San Jose, CA, May 2010
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43. L. Shah, R.A. Sims, C.C.C. Willis, P. Kadwani, J.D. Bradford, M. Richardson, "High-power spectral beam combination of thulium:fiber MOPAs," Directed Energy Professional Society (DEPS) Solid State Diode Laser Technology Review (SSDLTR) 2011.
44. C.C.C. Willis, J.D. Bradford, L. Shah, M. Richardson, "Measurement of thermally induced wavefront distortions using a Shack-Hartmann wavefront sensor," Directed Energy Professional Society (DEPS) Solid State Diode Laser Technology Review (SSDLTR) 2011.
45. R.A. Sims, P. Kadwani, C.C.C. Willis, J.D. Bradford, L. Shah, M. Richardson, "Ultrashort pulse thulium fiber lasers," Directed Energy Professional Society (DEPS) Solid State Diode Laser Technology Review (SSDLTR) 2011.
46. L. Shah, R.A. Sims, P. Kadwani, C.C.C. Willis, J. Chia, F. AlTal, D. Killinger, M. Richardson, "Transmission measurement in the 2 □m wavelength regime," Directed Energy Professional Society (DEPS) Solid State Diode Laser Technology Review (SSDLTR) 2011.
47. C. Willis, J.D. Bradford, L. Shah, and M. Richardson, "Measurement of wavefront distortions resulting from incidence of high-power 2 □m laser light," CLEO 2011, CTuE7.
48. R. A. Sims, P. Kadwani, L. Shah, and M. Richardson, "182 nJ all thulium fiber CPA system," CLEO 2011, JWA31.
49. C.C.C. Willis, J.D. Bradford, R.A. Sims, L. Shah, M. Richardson, J. Thomas, R.G. Becker, C. Voightländer, A. Tünnermann, and S. Nolte, "Monolithic narrow linewidth polarization-maintaining thulium fiber laser using femtosecond laser written fiber Bragg gratings," SPIE DSS 2011, Proceedings SPIE 80390H.
50. R.A. Sims, P. Kadwani, L. Shah, and M. Richardson, "Generation and amplification of femtosecond pulses in Tm:fiber," SPIE DSS 2011, Proceedings SPIE 80390K.
51. P. Kadwani, R.A. Sims, J. Chia, F. Altal, L. Shah, and M.C. Richardson, "Atmospheric gas detection using broadband mid-IR thulium fiber-based sources," SPIE DSS 2011, SPIE Proceedings 80390L.
52. R. Sims, P. Kadwani, L. Shah, and M. Richardson, "All thulium fiber CPA system with 107 fs pulse duration and 42 nm bandwidth," ASSP 2011, ATuD4.
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54. L. Shah, R.A. Sims, C.C. Willis, P. Kadwani, J. Bradford, and M. Richardson, “High power fiber lasers,” FILAS 2011, FWA4.
55. P. Kadwani, R. Sims, J. Chia, F. Altal, L. Shah, and M. Richardson, “Atmospheric propagation testing using broadband thulium fiber systems,” FILAS 2011, FWB3.
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57. R.A. Sims, P. Kadwani, L. Shah, and M. Richardson, “Generation and amplification of 350 fs, 2 m pulses in Tm:fiber,” SPIE Photonics West 2011, SPIE Proceedings 79141L.
58. P. Kadwani, J. Chia, F. Altal, R.A. Sims, C. Willis, L. Shah, D. Killinger, and M.C. Richardson, “Atmospheric absorption spectroscopy using Tm:fiber sources around two microns,” SPIE Photonics West 2011, SPIE Proceedings 79240L.
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60. M. Richardson, L. Shah, T.S. McComb, R.A. Sims, C. Willis, P. Kadwani, V. Sudesh, “Advanced Tm:fiber laser development,” Directed Energy Professional Society (DEPS) Solid State Diode Laser Technology Review (SSDLTR) 2010.
61. T.S. McComb, R.A. Sims, C.C. Willis, P. Kadwani, L. Shah, and M. Richardson, “Atmospheric transmission testing using a portable, tunable, high power thulium fiber laser system,” CLEO 2010, JThJ5.
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63. R.A. Sims, C.C. Willis, P. Kadwani, T.S. McComb, L. Shah, V. Sudesh, Z.A. Roth, M.K. Poutous, E.G. Johnson, and M. Richardson, “Spectral beam combining of 2 μm Tm fiber laser systems,” ASSP 2010, AMB6.
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65. T.S. McComb, L. Shah, C.C. Willis, R.A. Sims, P.K. Kadwani, V. Sudesh, and M. Richardson, “Thulium fiber lasers stabilized by a volume Bragg grating in high power, tunable and Q-switched configurations,” ASSP 2010, AMB2.
66. L. Shah, R.A. Sims, P. Kadwani, C.C. Willis, J.D. Bradford, Z. Roth, A.J. Pung, M.K. Poutous, E.G. Johnson, M.C. Richardson, “Integrated 100 W thulium fiber MOPA system,” SPIE DSS 2012, paper 8381-35
67. P. Kadwani, R.A. Sims, L. Leick, J. Broeng, L. Shah, M.C. Richardson, “CW and pulsed performance of Tm-doped photonic crystal fiber lasers,” SPIE DSS 2012, paper 8381-51
68. A. Schülzgen, C.J. Salvin, R.A. Sims, P.K. Kadwani, L. Shah, M.C. Richardson, R. Amezcua Correa, T.T. Alkeskjold, L. Leick, “Modal properties of photonic crystal fiber for high-power two micron fiber laser systems,” SPIE DSS 2012, paper 8381-04
69. C.J. Salvin, C. Loussert, T.T. Alkeskjold, L. Leick, R.A. Sims, P.K. Kadwani, L. Shah, M.C. Richardson, R. Amezcua Correa, A. Schülzgen, "Modal analysis of large-mode-area photonic crystal fiber for high power 2 um fiber lasers," Fiber Lasers and Applications (FILAS) 2012, paper FTh4A.5
70. P. Kadwani, N. Modshing, R.A. Sims, L. Leick, J. Broeng, L. Shah, M. Richardson, "Q-switched operation of a novel ultra-large mode area Tm3+ doped photonic crystal fiber," Advanced Solid State Photonics (ASSP) 2012, paper AM4A.18
71. P. Kadwani, N. Modsching, R.A. Sims, L. Leick, J. Broeng, L. Shah, M.C. Richardson, "Lasing in thulium doped polarizing photonic cyrstal fibers (PCF)," Photonics West 2012, paper 8237-107
72. P. Kadwani, R.A. Sims, L. Shah, M.C. Richardson, "Q switched PM Tm:fiber laser oscillator for mid-IR generation," Photonics West 2012, paper 8237-124
73. L. Shah R.A. Sims, P. Kadwani, C.C. Willis, J.D. Bradford, Z. Roth, A. Pung, M.K. Poutous, E.G. Johnson, M.C. Richardson, "Integrated 100-W polarized, narrow linewidth thulium fiber MOPA system," Photonics West 2012, paper 8237-25
74. P. Kadwani, J.D. Bradford, R.A. Sims, J.D. Musgraves, K.A. Richardson, L. Shah, M.C. Richardson, "High-power transmission characterization of chalcogenide glasses using a Tm:fiber laser system," Photonics West 2012, paper 8239-09

Number of Presentations: 74.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

1. US Patent 7,668,211, "Waveguide-Pumping Gain Guided Index Anti-Guided Fiber Lasers," V. Sudesh, T. McComb, M. Richardson, W. Hagemann, M. Bass, J. Ballato, and A. Siegman (2010).
2. "Gain-Guiding in Photonic Bandgap Fibers: A New Platform for Ultra High Power Lasers and Amplifiers," inventor: Tsing-hua Her (UNCC).
3. "Hybrid gain guiding in laser resonators," Inventors: T. McComb, M. Richardson, and V. Sudesh (UCF).

Patents Awarded

US Patent 7,668,211, "Waveguide-Pumping Gain Guided Index Anti-Guided Fiber Lasers," V. Sudesh, T. McComb, M. Richardson, W. Hagemann, M. Bass, J. Ballato, and A. Siegman (2010).

Awards

In addition to the aforementioned invited and plenary talks Principal Investigator John Ballato was elevated to the rank of Fellow of the American Ceramic Society (ACerS), the International Society of Optical Engineering (SPIE), and the Optical Society of America (OSA) during the duration of this program.

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Scott Iacono	0.50	
Stephen Budy	0.50	
Tim McComb	1.00	
Michael Hemmer	1.00	
Robert Sims	1.00	
Pankaj Kadwani	1.00	
William Hagermann	1.00	
Christina Willis	1.00	
Joshua Bradford	1.00	
Clemence Jollivet	1.00	
Faleh Altal	1.00	
K. Fan	1.00	
Mingzhen Tang	1.00	
FTE Equivalent:	**12.00**	
Total Number:	**13**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
Vikas Sudesh	1.00
Giorgio Turri	1.00
FTE Equivalent:	**2.00**
Total Number:	**2**

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
John Ballato	0.10	
Mike Bass	0.00	
Martin Richardson	0.00	
Tsing-hua Her	0.10	
Anthony Siegman	0.00	Yes
FTE Equivalent:	**0.20**	
Total Number:	**5**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
Nicholas Brabham	1.00	Materials Science
Dale Edmondson	1.00	Materials Science
Erik McKee	1.00	Optics
Cheree Armstrong	1.00	Optics
John Szilagyi	1.00	Optics
Dylan Mosses	1.00	Physics
FTE Equivalent:	**6.00**	
Total Number:	**6**	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period:	7.00
The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......	3.00
The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......	1.00
Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......	2.00
Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......	0.00
The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense	1.00
The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:......	1.00

Names of Personnel receiving masters degrees

NAME
Viktor Diefenbach
Tim McComb
Christina Willis
Michael Hemmer
Total Number: 4

Names of personnel receiving PHDs

NAME	
Scott Iacono	
Tim McComb	
William Hageman	
Total Number:	**3**

Names of other research staff

NAME	PERCENT_SUPPORTED
Paul Foy	0.20
Thomas Hawkins	0.20
Andrew James	0.20
Lawrence Shah	0.50
Y Chen	0.50
Hyun Su Kim	0.50
Dr. Gyu Ug Kim	0.50
Lanlan Gao	0.50
Xiangru Wang	0.50
FTE Equivalent:	**3.60**
Total Number:	**9**

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment which includes the technical report as well as list of publications, presentations and related program metrics.

Technology Transfer

High Power Fiber Lasers

Joint Technology Office High Energy Laser Interdisciplinary Research Initiative (JTO HEL MRI) Contract W911NF0510517 through the US Army Research Office

Principal Investigator: Dr. John Ballato, Clemson University
Co-Principal Investigators: Drs. Martin Richardson (UCF), Michael Bass (UCF), and Bryce Samson (Nufern)

This program focused on new materials and fiber designs towards the realization of 100+ kW class eye-safe fiber lasers based on the following guiding principles: large mode area, single mode, purity of polarization state, minimization of nonlinear effects, compatibility with all-fiber pumps, and high temperature buffer coatings. Over the duration of this program the most significant findings are discussed below in the following sections:

1. *Gain guided index anti guided fiber lasers*
2. *High temperature fiber coatings*
3. *Tm doped fiber lasers*
4. *Tm doped Photonic Crystal Fiber (PCF) lasers*

Gain guided index anti guided fiber lasers

This program pioneered the development, both theoretical and reduction to practice, of novel ultra-large mode area gain-guided index anti-guided fiber lasers. The theory and initial proof-of-concept fibers were reported previously. The content below focuses on more recent analysis relating to mode competition and increased efficiencies from GG+IAG fiber lasers. Specifically, in order to successfully increase the lowest order mode output power of fiber lasers, large mode area (LMA) fibers are being developed through a number of techniques to reduce such detrimental effects such stimulated Raman scattering, stimulated Brillouin scattering and optical damage. One of these techniques, gain guided, index anti-guided (GG+IAG) fibers, and was first shown to have potential as a LMA fiber laser through theoretical analysis. In subsequent experimental reports using fibers with Nd^{3+}-doped cores of diameter up to 400 μm. GG+IAG lasing was demonstrated with flash-lamp pumping, diode laser end pumping and power scalable diode laser side pumping.

Previously GG+IAG fiber lasers were restricted to having optical gain greater than that required for lossless propagation of the LP_{01} mode and a total gain less than that at which the LP_{11} mode would propagate without loss. These conditions gave rise to two inequalities that restricted the values of the output coupler reflectivity that could be used to ensure that only LP_{01} mode lased. The inequalities require that as the fiber core diameter is increased the reflectivity of output coupler is limited to a very narrow range approaching total reflection for very large fiber core diameters. This limitation on the output coupler is a drawback to achieving high output power from GG+IAG fiber lasers because the requirement of output coupler reflectivity of 100% contradicts that which would enable highest slope efficiency and optimized output power.

In this section, further evaluation is given to the theoretical model and experimental demonstration of GG+IAG fiber lasers. Transverse mode competition is shown to play a significant role in overcoming higher order modes when the output coupler reflectivity is out of the previously predicted range. This enables GG+IAG fiber lasers with high slope efficiency and output. Detailed theoretical analysis for transverse mode competition is presented with the corresponding experiment results showing significant improvement in the slope efficiency and output power while stably retaining beam quality M^2<2.

A GG+IAG fiber is one of the large mode area (LMA) fibers but it has a negative index-step from the cladding to the core that may be doped with active rare earth elements. The electric field E in the fiber is governed by Equation 1:

$$\nabla^2 E + k_0{}^2 \tilde{n}^2 E = 0 \qquad \text{Eqn. (1)}$$

with a complex valued refractive index, $\tilde{n} = n + j\, g/2k_0$, where the power gain coefficient g is treated as its imaginary part, k_0 is the vacuum wave number and n is the real refractive index. If one ignores intrinsic scattering losses, an optical mode can propagate without loss in a GG+IAG fiber when the gain coefficient in the active core medium is larger than its loss due to the index anti guided nature of the fiber construction. For a given mode m, this intrinsic propagation loss is denoted by mode propagation threshold g_{th}^m. The mode propagation condition in the GG+IAG fiber is then:

$$g^m \geq g_{th}^m \qquad \text{Eqn. (2)}$$

where the exact value of mode threshold g_{th}^m is obtained from mode theory for a GG+IAG fiber. Further,

$$g_{th}^m = g - 2\Im(\tilde{\beta}^m) \qquad \text{Eqn. (3)}$$

where $\Im(\tilde{\beta}^m)$ is the imaginary part of complex propagation parameter for the m-order mode $\tilde{\beta}^m$. The mode propagation threshold g_{th}^m is inversely proportional to the negative index-step, $-\Delta n$, and the core radius a. If the gain coefficient g is smaller than the mode dependent lossless propagation gain, g_{th}^m, Eq. (**Error! Reference source not found.**) shows that the imaginary part of the propagation parameter $\Im(\tilde{\beta}^m) < 0$, and the mode would therefore decay as it propagates in the axial direction and vanish after a distance of $-1/\Im(\tilde{\beta}^m)$. The approximate values of the lossless mode propagation threshold g_{th}^m for the lowest two modes LP_{01} and LP_{11} are:

$$g_{th}^{01} = \sqrt{\frac{133.8}{2n_0^3(-\Delta n)}}\frac{\lambda^2}{(2\pi)^2 a^3} \qquad \text{Eqn. (4)}$$

$$g_{th}^{11} = \sqrt{\frac{862.2}{2n_0^3(-\Delta n)}}\frac{\lambda^2}{(2\pi)^2 a^3} \qquad \text{Eqn. (5)}$$

when the quantity $\Delta N \equiv \left(\frac{2\pi a}{\lambda}\right)^2 (2n_0)\Delta n \le -50$. Consider now a GG+IAG fiber with a core diameter of 200 μm and a cladding diameter of 400 μm, if the gain coefficient in the core is large enough to compensate for the corresponding loss as in Eqn. (**Error! Reference source not found.**), the four lowest order modes patterns are as shown in Figure 1.1 and are similar to fiber modes in ordinary index guided fibers.

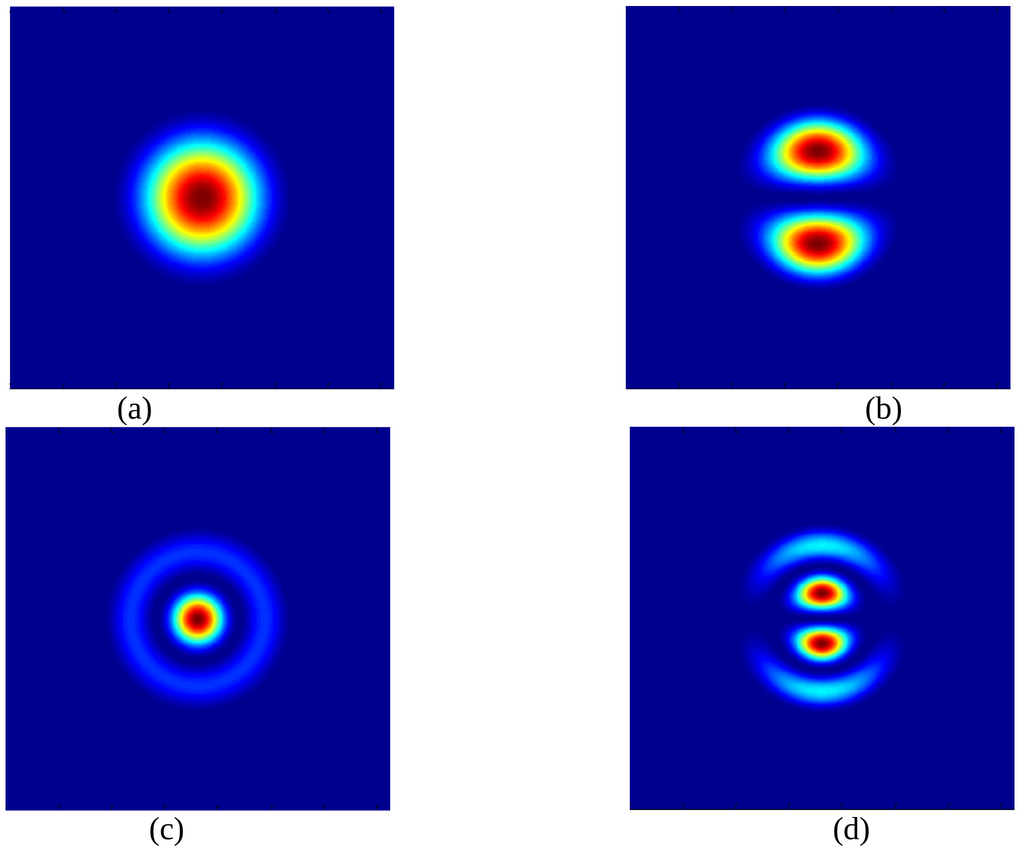


Figure 1.1: Calculated intensity profile of LP_{01} (a), LP_{11} (b), LP_{02} (c) and LP_{12} (d) modes in a GG+IAGfiber with a core diameter of 200μm

Mode competition in GG+IAG fiber lasers

There will be a number of modes propagating in the fiber when their gain coefficients are assumed to be large enough to allow lossless propagation. In this section, we discuss the mode competition between the two lowest order modes, LP_{01} and LP_{11}. The analysis that follows can then be extended to the case of multi-mode oscillation.

The gain coefficient is inversely proportional to the total power of all the modes having either forward or backward propagation. To be the common source of all modes that oscillate the inverted population is consumed to support the amplification. The ratio of LP_{01} and LP_{11} gain coefficients along the fiber is easily obtained as

$$\frac{g^{01}}{g^{11}} = \frac{A^{01}}{A^{11}} > 1 \qquad \text{Eqn. (6)}$$

with the approximation that $P_l >> I_l^{sat} A^m$. The LP_{01} mode has a larger mode area and can benefit from more of the inverted population as it propagates along the fiber. The ratio of LP_{01} and LP_{11} oscillation gain coefficient then is:

$$\mathbf{1}\,\frac{g_{osc}^{01}}{g_{osc}^{11}} = \frac{\dfrac{-\ln R_1 R_2 + \alpha_0}{2l} + g_{th}^{01}}{\dfrac{-\ln R_1 R_2 + \alpha_0}{2l} + g_{th}^{11}} < 1 \qquad \text{Eqn. (7)}$$

Since $g_{th}^{01} < g_{th}^{11}$ the lower order LP_{01} mode requires less gain to oscillate. The round trip gain of the LP_{11} mode is found to be

$$\oint \boldsymbol{g}^{11}(\boldsymbol{z})\,\boldsymbol{dz} = \frac{g_{osc}^{01}}{g_{osc}^{11}} \frac{A^{11}}{A^{01}} 2 g_{osc}^{11} l < 2 g_{osc}^{11} l \qquad \text{Eqn. (8)}$$

Therefore, the oscillation condition cannot be established for higher order modes at the same time as the lowest LP_{01} mode because of the constant inequality $g_{th}^{01} A^{11} < g_{th}^{11} A^{01}$. Although the LP_{11} mode can propagate with no net loss in the GG+IAG fiber when its gain coefficient g^{11} is higher than its GG+IAG mode threshold, g_{th}^{11}, it cannot oscillate in the fiber laser because the effective gain coefficient along the fiber $\oint \boldsymbol{g}^{11} - \boldsymbol{g}_{th}^{11} \boldsymbol{dz}$ cannot overcome the loss to the laser through the output coupler. Consider the ratio Γ defined as the difference between oscillation gain threshold $2 g_{osc}^{11} l$ and the round trip gain, $\oint \boldsymbol{g}^{11}(\boldsymbol{z})\,\boldsymbol{dz}$ divided by the oscillation threshold for the LP_{11} mode.

$$\Gamma = \frac{2 g_{osc}^{11} l - \oint \boldsymbol{g}^{11}(\boldsymbol{z})\,\boldsymbol{dz}}{2 g_{osc}^{11} l} \qquad \text{Eqn. (9)}$$

This ratio gives a measure of the likelihood of the LP_{11} mode oscillating. As the difference between gain threshold and round trip gain increases it becomes more difficult for a high order mode to oscillate. Employing the equations above and neglecting the difference between A^{11} and A^{01}, gives Γ as:

$$\Gamma = \frac{\sqrt{\dfrac{862.2}{2 n_0^3 (-\Delta n)}} - \sqrt{\dfrac{133.8}{2 n_0^3 (-\Delta n)}}}{\dfrac{-\ln R_1 R_2 + \alpha_0}{2l} \Big/ \dfrac{\lambda^2}{(2\pi)^2 a^3} + \sqrt{\dfrac{862.2}{2 n_0^3 (-\Delta n)}}} \qquad \text{Eqn. (10)}$$

For the LP_{11} mode, Γ is inversely proportional to a^3 and to $-\ln(R_1R_2)$ so that for large core radii fibers higher order mode oscillation is more likely. Also, if the output coupler reflectivity is high Γ is smaller and higher order mode oscillation could occur.

We assume a fiber laser system with a GG+IAG fiber with core diameter of 200 μm, an index step of -0.0045 from cladding to the core, a fiber length l = 4 cm, an absorbed pump power P_p =100 W, and a Snell's law reflection loss $\alpha_0 = 5\%$. Two output couplers ($R = 90$ % and 50 %) are chosen to represent two cases: 1) where no LP_{11} propagates since $g^{11} < g_{th}^{11}$ and 2) when the LP_{11} mode experiences lossless propagation where $g^{11} \geq g_{th}^{11}$. By solving the coupled differential equations above, for steady state oscillation, the average gain coefficient, $\bar{g}^m = \oint \boldsymbol{g}^{01/11}(\boldsymbol{z})\boldsymbol{dz}/2l$, mode propagation threshold, $g_{th}^{01/11}$, oscillation gain coefficient, $g_{osc}^{01/11}$, and laser output power of each mode can be calculated and are listed in Table 1. The gain coefficient distributions $\boldsymbol{g}^{01/11}(z)$ are also shown in Fig. 1.2 and Fig. 1.3 for 90%, and 50% output couplers, respectively.

Table 1 Calculated quantities for a 200 μm core diameter GG+IAGfiber laser

Output Coupler R	Mode	$\bar{g}^m$ m^{-1})	g_{th}^m (m^{-1})	g_{osc}^m (m^{-1})	P_{out}^m (W)
90%	LP 01	3.72	1.76	3.70	17.32
	LP 11	3.38	4.47	6.41	1.5e-3
50%	LP 01	11.07	1.76	11.05	37.69
	LP 11	10.07	4.47	13.76	5.6e-3

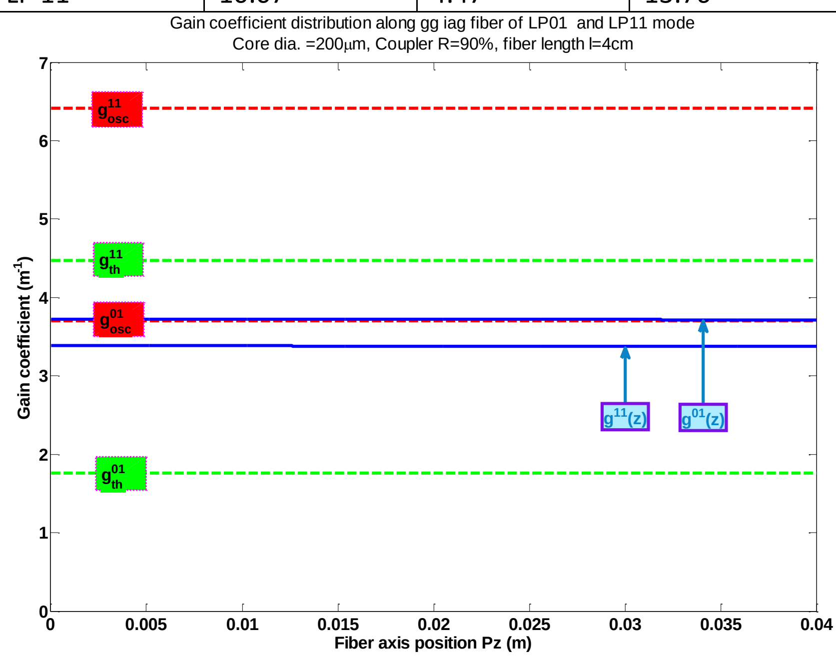


Figure 1.2 Calculated gain coefficient distribution along the length of the fiber laser using a 90% R output coupler.

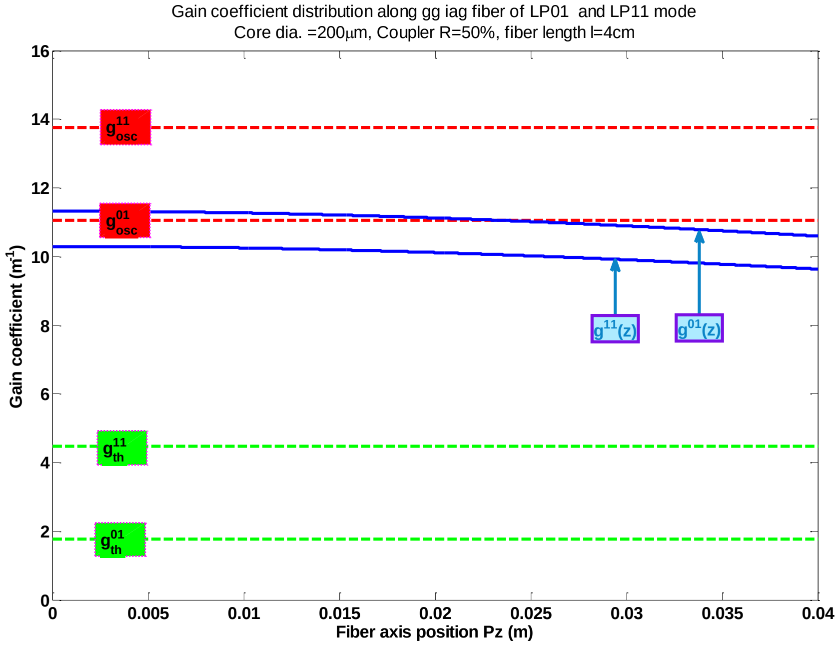


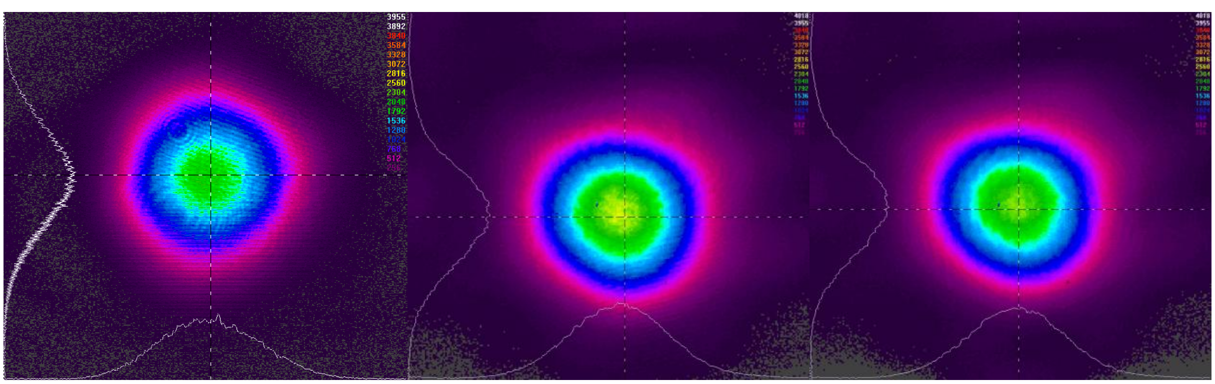
Figure 1.3 Calculated gain coefficient distribution along the length of the fiber laser using a 50% R output coupler.

In the case of fiber laser with a R = 90% output coupler, numerical results are listed on the top two rows in Table 1 and plotted functions are shown in Figure 1.2. Owing to the power saturation the gain coefficient is inversely proportional to the total power when the power of LP_{01}mode achieves steady state lasing. The gain coefficient of the LP_{01} mode, g^{01}, remains close to the oscillation gain threshold g^{01}_{osc}. Equally important, the gain coefficient of the LP_{11} mode g^{11} is not only smaller than g^{01} but is also smaller than its mode propagation threshold, i.e. $g^{11} < g^{11}_{th}$. According to the mode propagation condition above, the LP_{11} mode cannot propagate without loss, much less oscillate, i.e. $g^{11} << g^{11}_{osc}$. Consequently, the fiber laser can only support the lowest order single mode propagation and oscillation. The last column in Table 1, giving the computed output power also shows that the LP_{01} mode alone is able to lase.

In the case of the GG+IAG fiber laser with 50% R output coupler, numerical results are listed in the last two rows in Table 1 and functions for the gain coefficient are shown in Figure 1.3. The gain coefficient of the LP_{11} mode is larger than its lossless mode propagation threshold, i.e., $g^{11} > g^{11}_{th}$, and the single mode propagation condition is not satisfied. i.e. the LP_{11} mode can propagate along the fiber with no loss. However, it is smaller than its oscillation gain threshold, i.e., $g^{11} < g^{11}_{osc}$, which is the key condition for laser oscillation. According to the above, the LP_{11} mode cannot oscillate. From Table 1, the power of the LP_{11} mode is a very small part of the total power. The LP_{01} mode contributes the vast majority of the output power. Even though the higher order mode can be delivered by the GG+IAG fiber, the lowest order LP_{01} mode contributes the vast majority of the output laser beam. The fiber laser works in the state of lowest order mode oscillation and lowest order mode output. There is only some amplified spontaneous emission of the higher order mode, but that can be neglected.

The experimental procedure for studying the role of transverse mode competition is similar to that previously demonstrated in this program using a scalable LD side pump GG+IAG fiber laser. The resonator is composed of a flat total reflector and a flat partial reflective output coupler with a straight 4 cm length GG+IAG fiber embedded in a V-groove in a water-cooled copper block. A linear diode laser array manufactured by Dilas was the side pump source. It was driven by a pulsed power supply at a rate of roughly 1 Hz with pulse duration of 3.71 ms emitting at 808 nm with narrow line width. The GG+IAG fibers used have a core diameter of either 100, 200 or 300 μm and a cladding refractive index of 1.5734, a negative index step difference of -0.0045 and core of Q100 phosphate glass doped with 10% wt. Nd^{3+}. Lasing took place at 1054 nm with 2 nm line width.

The GG+IAG fiber laser must be aligned properly so that the lowest LP_{01}mode alone oscillates. This condition of alignment is achieved by first aligning the output coupler mirror so that some lasing is detected by the laser beam analyzer. When the mirrors were so aligned emission, possibly multi-mode emission, could be observed. Such roughly aligned mirrors induce larger resonator loss so that the ratio of oscillation gain coefficients $g_{osc}^{01} / g_{osc}^{11}$ is close to 1. Under this condition mode competition could not contribute, effectively allowing multi-mode lasing to take place. Once some lasing was observed the output coupler was aligned to achieve a round, symmetric pattern. When this was achieved measurement of the beam quality, M^2, was carried out to confirm single lowest order mode operation. After suitable alignment to obtain a circularly symmetric beam profile, it was measured with both Pulnix 745 and Sentech 700 CCD cameras and processed with Spiricon Laser Beam Analysis software. The beam profiles shown in Figure 1.4 (a-c) were captured from three GG+IAG fiber lasers having the same coupler of 45% reflectivity but different core diameters of 100, 200 and 300 μm, respectively. (Note: to let the beam profile occupy most of the active area of the CCD arrays the locations of the CCD cameras were different for these three fibers. The beam sizes shown in Fig. 1.5 do not provide a comparison of mode diameter from each fiber laser. These three GG+IAG fiber lasers produced mode patterns that are Gaussian-shaped and stable even well above lasing threshold.



(a) (b) (c)

Figure 1.4 Measured single lowest order mode patterns lasing from GG+IAGfiber laser using a 45% R output coupler. The core diameters 100 μm (a), 200 μm (b) and 300 μm (c), respectfully.

Table 2 Quantities measured for 100, 200 and 300 μm core diameter GG+IAGfiber lasers

Core Dia.	Coupler	M^2_x	M^2_y	Threshold Power (W)	Slope efficiency	P_{out} max
100μm	37%	1.60	1.44	26	4.09%	5.93
	45%	1.45	1.44	21	3.28%	4.64
	90%	1.34	1.34	12	0.62%	0.93
200μm	37%	1.44	1.35	31	11.08%	14.04
	45%	1.31	1.31	27	7.57%	10.73
	90%	1.25	1.23	12	1.13%	1.94
300μm	37%	1.89	1.95	27	26.4%	32.35
	45%	1.60	1.71	25	12.35	18.19
	97%	1.32	1.35	7	0.74%	1.22

In our GG+IAG fiber laser experiment we used three output couplers with reflectivities of 37, 45 and 90%. These were used with each of these three GG+IAG fibers. With an input pump power of up to 50 W we measured the beam quality for the nine combinations of output coupler and fibers using the standard means to determine beam quality factor, M^2. The results are summarized in Table 2. For each combination the output laser power was measured using an Ophir Laserstar power/energy meter with a PE25-BB pyro electric detector head. Slope efficiencies in each case were calculated using a numerical linear fitting method and are also listed in Table 2.

The M^2 values for all output couplers with each fiber are less than 2. In earlier work a very strong restriction was placed on the output coupler reflectivity so that the total gain was less than the threshold gain for the LP_{11} mode to propagate with no loss. The M^2 values for the 100, 200 and 300 μm fibers were 1.5, 1.2, 1.8, respectively, when using the strict condition on output coupler reflectivity. The measured values of M^2 as listed in Table 2 using output couplers with reflectivities outside the ranges noted are not significantly different than these values. This indicates that the earlier restriction, while correct, was too strong. Mode competition can result in lowest order mode oscillation. Table 2 shows, for example, that the 200 μm GG+IAG fiber laser with an output coupler with higher reflectivity has a better beam quality. From the equations above we see that the parameter Γ which is a criterion for mode competition is proportional to the output coupler reflectivity R_2. For a higher reflectivity, the value of Γ is larger and mode competition can play a more effective role on restricting laser oscillation to the lowest order mode only.

Given a laser cavity with a constant output coupler reflectivity we analyzed the beam quality shown in Table 2. The beam quality is worse for a larger core diameter. From above the ratio parameter Γ is inversely proportional with fiber radius a^3. For a larger core radius, the value of Γ is smaller and mode competition will be less effective in fixing the mode that oscillates, leading to a lower beam quality or larger M^2.

The slope efficiency is inversely proportional to output coupler reflectivity and proportional to core diameter. An inverse proportionality to output coupler reflectivity is related to the fact that lower transmission allows larger laser output. There are two main reasons leading to the proportional relation between slope efficiency and core diameter. First, GG+IAG fibers with larger core have smaller mode propagation loss that is inversely proportional to the cube of the diameter. Hence a larger core diameter leads to larger slope efficiency. Second, in our experiments a larger core fiber allowed a larger window to be polished to accept more pump power from the diode laser array. This allowed more efficient pumping resulting in higher slope efficiency. The slope efficiency improved from 4.3 % in previous MRI team work to 26.4 % more recently.

Theoretical and experimental evidence is presented showing that mode competition in GG+IAG fiber lasers enables excellent beam quality output with improved slope efficiency. In a GG+IAG fiber gain guiding can compensate for index anti-guiding and modes can propagate without loss largely confined to the core. In earlier work we placed a restriction on the design of the resonator for a GG+IAG fiber laser that demanded that the total gain not exceed that of the second lowest order mode. If it did then the two lowest order modes could propagate without loss.

However, as a consequence of gain saturation which is related to the total power of all possible modes including both directions of propagation, the gain coefficients for each mode are all around the value of first order mode oscillation gain coefficient. For a higher order mode, the value of its gain coefficient could be larger than its threshold for lossless propagation in the fiber. However, the higher order mode would not oscillate and contribute to laser output because its gain coefficient is always less than its oscillation gain coefficient required for laser oscillation. In other words, higher order modes may propagate with no loss in the GG+IAG fiber, but cannot oscillate and contribute to laser output because its gain is insufficient for oscillation Experimental evidence for the role of mode competition in GG+IAG fiber lasers is presented for fibers of different core diameter and three output coupler reflectivities. For these fibers the reflectivities used should not have allowed lowest order mode oscillation only according to an earlier strong restriction that limited total gain to less than that of the loss less propagation gain of the second higher order mode. However, in all cases the output beam quality is all less than 2. Transverse mode competition plays a very significant role in sustaining the beam quality while giving much improved slope efficiency to 26.4%.

High temperature fiber coatings

Especially when employed in non-traditional environments, such as HELs, the thermal and mechanical robustness of the optical fibers is of major concern and the polymeric fiber coatings can be the limiting factor in the utility of the fiber. The purpose of this work was to develop coatings that permitted higher operational temperatures from fiber lasers. Specifically, a convenient route to enhancing the thermal degradation on-set temperature of existing commercial optical fiber coatings is presented. UV curable acrylate coatings were modified through the addition of a multi-functional cross-linking agent and are shown to increase their degradation temperature by 65 ˚C without any degradation in the mechanical or optical properties of the resultant fiber. Such enhanced thermal robustness in coatings is important for optical fiber applications in high energy laser (HEL) systems and selected higher temperature sensing environments.

For decades, polymeric coatings have been applied to optical fibers. The coatings provide mechanical protection to the pristine surface of the as-drawn glass. With a few limited exceptions, the fiber industry has largely relied on an acrylate-based polymer system due to its relatively low cost and its ability to be cured at high speed on-line using ultraviolet (UV) light. Cross-linked polymers have been extensively studied and offer beneficial properties such as good fracture strength, high modulus, increased solvent stability, better scratch resistance, reduced oxidation, and improved thermal degradation.

However, as fibers are finding use in more extreme environments, there is a growing need for coatings that exhibit greater thermal stability while not adversely affecting the overall mechanical or optical properties of the fiber. Rather than introduce a new polymer into what is a well-established industry, this work takes off-the-shelf UV curable acrylates accepted by the industry and enhanced their thermal stability through a simple additive. More specifically, reported here is a method to easily modify a wide range of commercially available acrylate resins through the addition of a multi-functional cross-linker.

Desolite single coating (#3471-3-14), a well-established optical fiber coating, was purchased from DSM Desotech, Inc. (Elgin Ill.). Dipentaerythritol penta-/hexa-acrylate was purchased from Sigma-Aldrich, and was chosen due to a high level of cross-linking functionality. Thereby small quantities can be added with the greatest change in properties. Preliminary tests involved blending different weight loadings (wt %) of the penta-/hexa-functional acrylate cross-linker with DSM resin at the selected amounts. Samples were mixed with a mechanical shaker for 12–24 hr to ensure proper mixing. Films were prepared by drop casting and spin casting the prepared solutions and then curing under a UV lamp for 6–8 hr to ensure complete polymerization.

Thermal stability was predicted using dynamic thermal gravimetric analysis (TGA) obtained using a TA Hi-Res TGA2950. Thermal decomposition temperatures were obtained at a temperature rate of 10 ºC/min in air. The degradation temperature (T_d) was defined as the temperature where the onset of weight loss deviated from 100%. The refractive index was acquired from spin cast films on glass substrates obtained at 633 nm using a Metricon Prism Coupler 2010.

Coating solutions were prepared in larger volumes for subsequent coating onto a silica optical fiber (~50 mL total volume). Mixing was ensured by a mechanical shaker overnight, followed by filtering with a 1 μm filter and centrifugation (10,000 rpm) to remove all bubbles. Solutions were taken immediately to the draw tower for use after centrifugation.

A 26 mm diameter F300 silica rod, manufactured by Heraeus Tenevo (Buford, GA), was used in all draw experiments. The optical fibers used in this study were drawn at Clemson University using a commercial grade Heathway draw tower. The following details were used on all fiber and coating draws: the draw temperature was 2025 ºC, a laser gauge measured 125 ± 0.5 μm for all fiber diameters, pressure driven coating system using pressures from 0.8 to 1.0 bar with coating head die sizes; 375 μm (entrance die) with either 275 μm, 325 μm, or 350 μm (exit dies) was used to apply to the fiber while drawing, a UV lamp operating at 150 to 175 Watts/inch, a second laser gauge measured the average thickness of the coating (ranged from 200.8 to 241.7 μm), and a spool to collect the fiber, from beginning to end.

The strength and fatigue behavior of the fibers with zero and 20 wt % of crosslinker in the coating have been characterized with two-point bending using standard test procedures. In addition, the strength distributions have been measured in uniaxial tension with a gauge length of 0.5 m, also using standard test methods. Coating strip force measurements have been made to characterize coating adhesion and strippability, using a standard test method. Since strength and fatigue (and, to some extent, strip force) are sensitive to temperature and humidity, all measurements were made in a controlled environment of 23 ± 0.2 °C, 50 ± 5% humidity.

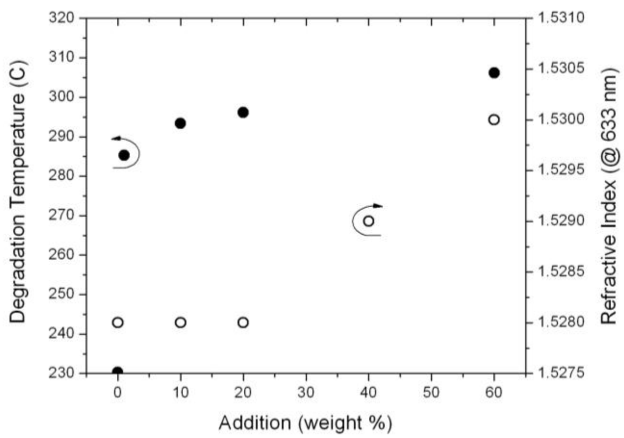


Figure 2.1. Onset of degradation temperatures measured by TGA in air (●) and room temperature refractive index (○), at a wavelength of 633 nm, measured as a function of multi-functional cross-linker concentration.

Spin cast films were prepared on glass substrates and fully cured under a UV lamp for each loading level. The results are shown in Figure 2.1. No change in refractive index was found until a loading greater than approximately 30 wt % cross-linker was achieved.

Thermal gravimetric analysis (TGA) was used to estimate the thermal stability of the acrylate coating containing zero up to 60 wt % multi-functional cross-linker addition. Although only dynamic thermal analysis was performed, a more thorough study would entail isothermal experiments at numerous temperatures. However, it is necessary to know the highest temperature at which a coating continues its efficacy. The thermal stability may be defined in many ways; the highest temperature before degradation is essential in defining an appropriate performance level for a explicit period of time. As shown in Figure 2.1 and 2.2, the onset of thermal degradation increases with continued addition of the multi-functional acrylate cross-linker. With the addition of only 1 wt % of the multi-functional acrylate cross-linker, the thermal degradation temperature raises from 230 ºC to 285 ºC in air; a 55 °C increase. Thermal degradation occurs for all samples beyond 300 °C, thereby leading to catastrophic weight loss and possible separate weight loss mechanisms as seen by the multi-modal decrease. Further studies would be necessary to convolute the exact degradation mechanism. Nevertheless, at lower temperatures a smooth minimal weight loss can be observed indicating complete cross-linking and curing.

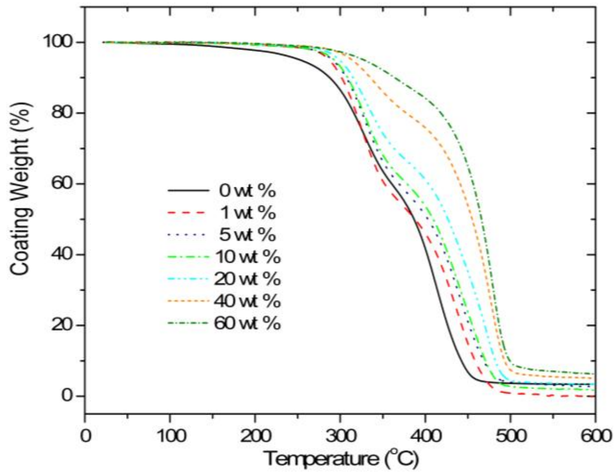


Figure 2.2. Dynamic thermal gravimetric analysis curves obtained for acrylate coating with different amounts of multi-functional cross-linker (10 °C/min).

The subcritical crack growth (fatigue) behavior of fiber coated with polymer containing zero and 20 wt % of cross-linker has been measured using two-point flexure. The results in Figure 2.3 show how the strength varies with loading rate (as characterized by the faceplate velocity). The slope of the log-log plot is used to determine the stress corrosion susceptibility parameter, n, which is found to be 20.6 [20.0 – 21.2] and 20.3 [19.6 – 21.0] for the zero and 20 wt % cross-linker coatings respectively; the numbers in brackets represent a 95% confidence interval for the estimates of n. While the fatigue behavior of the two specimens is statistically indistinguishable, the coating containing the cross-linker results in a somewhat higher strength fiber.

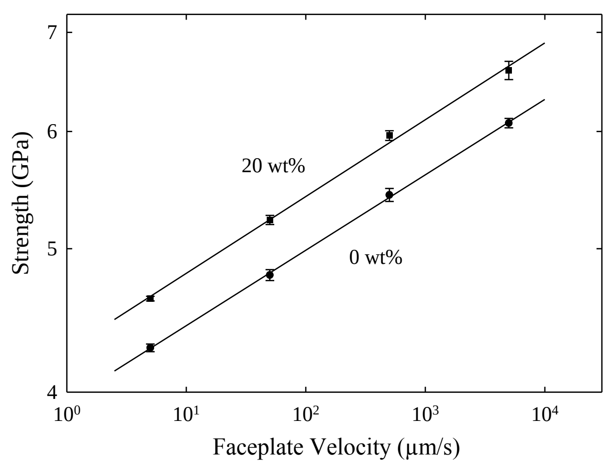


Figure 2.3. Fiber strength measured in two-point bending as a function of faceplate velocity for coating with and without 20 wt % of cross-linker.

Two-point bending was used for these measurements since it has an effective test length of one to a few tens of microns. As a result the occasional weak defect that is due to extrinsic processing defects are not observed and the method is more sensitive to the glass/coating interface itself, which is the topic of importance here. However, tensile measurements have also been made to ensure that the cross-linker does not cause an excessive number of weak failures due to, for example, incorporation of dust into the coating. Figure 2.4 shows a Weibull probability plot for 0.5 m tensile specimens and it is observed that the cross-linker has an insignificant effect on the strength distribution. Overall, the cross-linker does not have any negative impact on the short term strength and fatigue behavior.

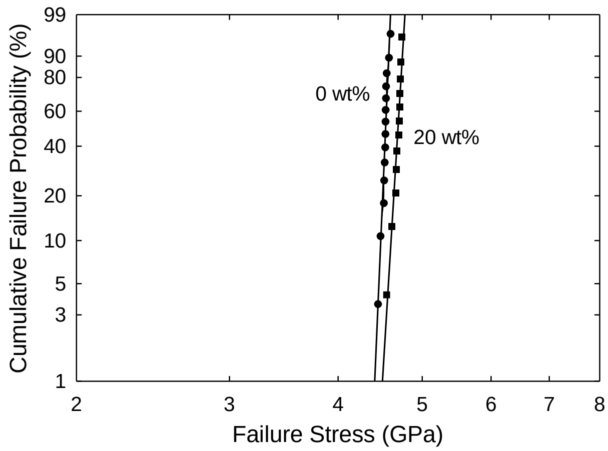


Figure 2.4. Weibull plot of the strength distributions measured in uniaxial tension and a gauge length of 0.5 m at a stress rate of 30 MPa/s for fiber with coatings containing 0 and 20 wt % of cross-linker.

In general, UV-curable polymer coatings do have some effect on fatigue – typical values for *n* are around 20 to 25 but can sometimes be as high as 30 for some coatings – but the effects are not dramatic. In contrast, the zero stress aging behavior can be far more sensitive to the nature of the coating. During aging in aggressive environments (high temperature and/or high humidity or water activity) strength degradation can be observed to occur beyond some incubation time; degradation is caused by corrosion of the glass surface by moisture. The corrosion causes surface roughness which acts as a source of stress concentrators, so degrading the strength. The time of onset of the zero stress aging "knee" is known to be very sensitive to the nature of the coating. Ideally, any modification to the coating should not adversely affect the zero stress aging behavior.

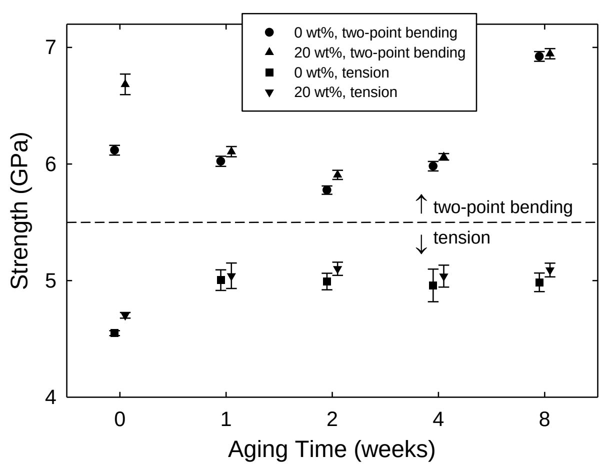


Figure 2.5. Strength measured in two-point bending (faceplate speed 5000 μm/s) and tension (stress rate 30 MPa/s) as a function of zero-stress aging time in 85 °C, 85% humidity environment.

Figure 2.5 shows how the strength varies with aging time under zero stress in an 85 °C, 85% humidity environment (an industry standard test condition for enhanced thermal aging) for fibers coated with polymer coating with 0 and 20 wt % cross-linker. Strength was measured in both two-point bending and 0.5 m gauge length tension. Although the results for bending and tension are significantly different (due to how the different effective test lengths interact with the somewhat sparse population of flaws) the amount of cross-linker does not affect the performance. The stress corrosion parameter, *n*, measured in two-point bending (Figure 2.6), while increasing with aging time, is essentially independent of the amount of cross-linker. These results show that the amount of cross-linker in the coating does not adversely affect the zero-stress thermal aging behavior, at least in regard to current industry standard requirements.

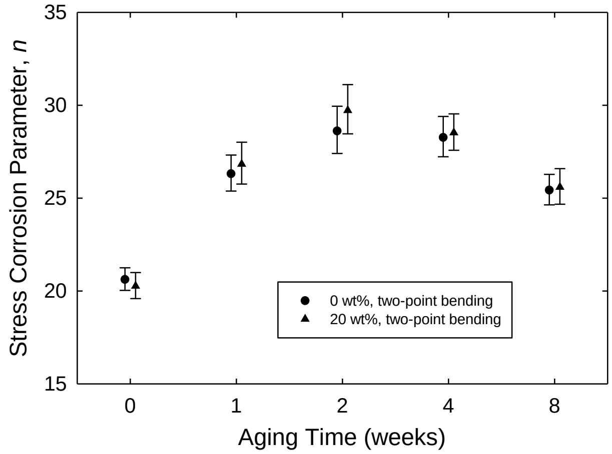


Figure 2.6. Stress corrosion parameter measured by dynamic fatigue in two-point bending as a function of zero-stress aging time in 85 °C, 85% humidity environment.

In conclusion for this section, the thermal degradation temperature of commercially available acrylate-based optical fiber coatings has been improved by the addition of a single component drop-in modifier. The onset for thermal decomposition temperature increased by 65 °C through the addition of modest amounts of multi-functional acrylate cross-linker. A range of mechanical tests showed that the overall strength, dynamic fatigue parameter, and zero-stress aging performance were unaffected by the additive or slightly improved. Additional acrylate resins are also of interest and are being explored for lower refractive index coatings.

Tm doped fiber lasers

This program made significant advances to the materials, fiber lasers, and commercialization associated with eye-safe Tm^{3+}-based systems. Provided below is a summary fiber laser efforts and is followed by a section on PCF-based analogs.

Free-space coupled Tm fiber laser

Dichroic mirrors as shown in Figure 3.1 were used to form the laser cavity. The pump-end of the fiber was sandwiched between cooled copper plate and a part of the fiber was in water bath as shown in Figure 3.2. We demonstrated 45 W of 2 μm laser, with slope efficiency ~41%. Beam quality was multimode due to poor thermal management. The pump-end of the fiber glowed due to thermal load (Figure 3.2) and damaged at an incident pump power of 120 W. The heat handling capability of the fiber can be increased by splicing undoped fiber at both ends of the gain fiber as it is used in the following experiment.

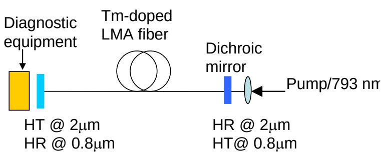


Figure 3.1. Schematic of the fiber laser set up

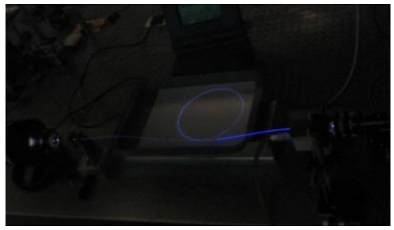


Figure 3.2. Tm-doped fiber laser using free space coupling of pump.

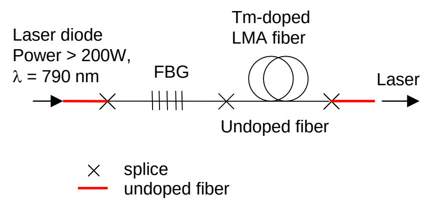


Figure 3.3. Schematic of Tm LMA fiber

Narrow linewidth Tm fiber laser using FBG

Using Nufern's Tm-doped large mode area (LMA) fiber module we demonstrated ~95 W of 2 μm laser at a slope efficiency of ~50%. Nearly diffraction limited beam quality was observed. Schematic of the setup is shown in Figure 3.3. The LMA Tm fiber was 5.5 m long with a fiber Bragg grating (FBG) spliced to it. The FBG acted as a dichroic mirror, allowing the pump at 790 nm to transmit whereas acting as a narrow band high reflector (HR) mirror at 2050 nm. The double clad Tm-doped fiber has a 25 μm core diameter with 0.1 NA and 400 μm cladding. Both ends of the module had ~2.0 m of undoped fiber for better thermal management. Canopus (Spectra-Physics) fiber-coupled high power laser diodes were used to pump the gain module.

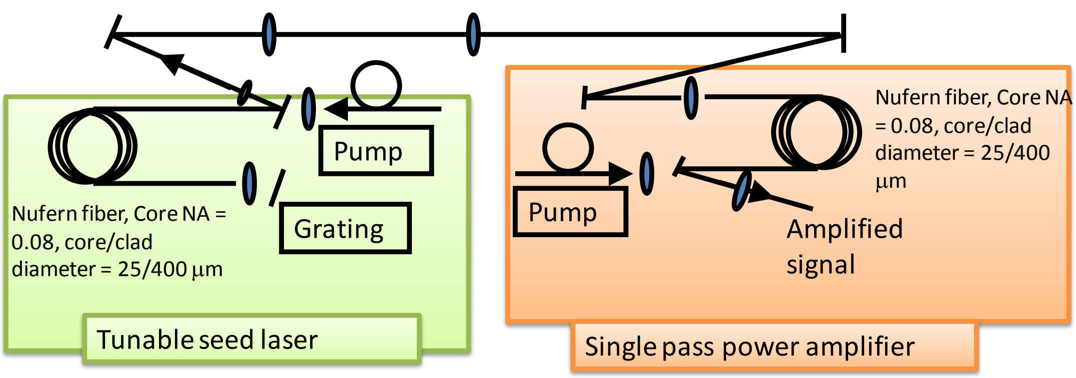


Figure 3.4. Schematic of the master oscillator power amplifier (MOPA) system.

Shown in Figure 3.4 is a schematic of the MOPA setup consisting of a tunable seed source and a single pass power amplifier.

High power, tunable, CW, narrow line thulium fiber laser

The fiber used for this experiment (Nufern, Inc.) was fabricated from SiO_2, and had a 400 μm flat-to flat, 0.46 NA octagonal shaped cladding and a 25 μm diameter, 0.08 NA circular core. The length of the doped region of the fiber (~ 4.0 wt. % Tm^{3+}) was ~ 5 m long with an ~ 2 m section of undoped fiber whose NA and core size matched with doped fiber on each end to help reduce thermal stress on the directly end pumped fiber. The 5 m gain region of the fiber was wrapped around a water cooled 11 cm diameter Al heat sink to provide better thermal management and hence improve laser efficiency, since the cross-relaxation process in Tm^{3+} is highly temperature dependent. The pumped end of the fiber was held in a water cooled Cu clamp. Both fiber ends were cleaved using Vytran LDC-200 cleaver. The laser resonator was formed on one side by the Fresnel reflection from the cleaved end of the fiber and on the other side by a 50 mm focal length AR coated Aplanat lens followed by a grating blazed at 1850 nm is used as an HR mirror. Light from a 795 nm Spectra-Physics 40W 0.22 NA, 400 μm core fiber-coupled diode bar was launched through a dichroic dielectric mirror designed to be HR at 2 μm and highly transmissive at 795 nm at a mirror angle of ~22° and into the fiber by way of two sets of infinite conjugate ratio fast achromatic doublet pairs with an NA of 0.26 and a working distance of 84 mm. Wavelength tuning of the oscillator with the grating over >100 nm (1987 nm - 2095 nm) (Figure 3.5) with output powers of 6-11 W dependent on the wavelength (Figure 3.6).

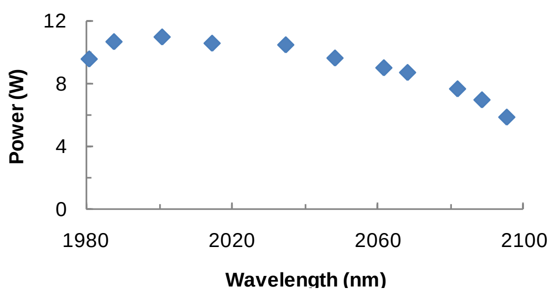


Figure 3.5. Tunability curve of the seed laser

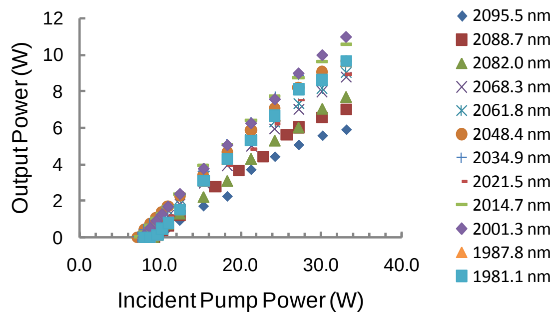


Figure 3.6. Output power versus incident total pump power at various wavelengths.

Master Oscillator Power Amplifier

For the single pass 100 W power amplifier, a train of lenses was used to match the spot size and the NA of the core of the amplifier gain fiber. Light from a 795 nm Spectra-Physics 200 W 0.22 NA, 400 um core fiber-coupled diode bar was launched through a dichroic dielectric mirror designed to be HR at 2 um and highly transmissive at 795 nm at a mirror angle of ~22° and into the fiber by way of two sets of infinite conjugate ratio fast achromatic doublet pairs with an NA of 0.26 and a working distance of 84 mm. The 2-mm seed-light is focused on the tip of a power amplifier. The amplifier is made of Nufern LMA fiber same as that used for making the seed laser. The amplifier module is similar to that used in building the seed laser, except that the length of the fiber is 7 m to absorb most of the power and ends of the undoped fibers spliced to the gain fibers are angle cleaved ($\sim 5^0$) to avoid parasitic oscillation. At an output power of ~25 W the laser system was life-tested for its power stability. Power was stable for an hour before the current was shut down. The beam quality was not measured however, it was estimated to have an M^2 of < 2. Pump light in the clad needs to be completely stripped off. An output power of 100 W was achieved with full power of seed injected into the amplifier [Figure 3.7] however the fiber got damaged at the spliced location of fiber. The recoating of the spliced portion of the fiber will increase the power handling capability, which we are doing using an extended length recoater, Vytran PTR-200. Currently the effort is on to scale the power up to 200 W.

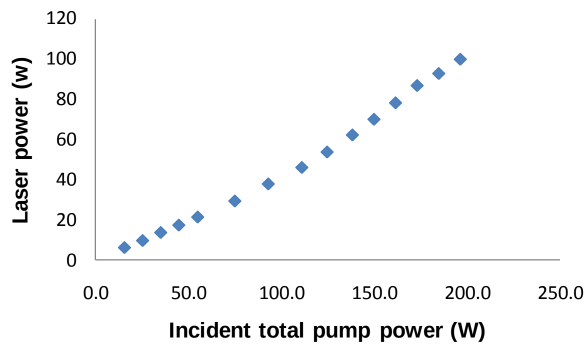


Figure 3.7. Output power versus incident total pump power.

High power (~200 W) Tm: silica fiber laser oscillator

As mentioned above the power amplifier of the system is constructed from ~7 meters of Nufern 0.08 NA, 25 micron core, 400 micron clad thulium doped fiber with ~2 meters of undoped numerical aperture and core size matched fiber spliced on the ends to provide better thermal performance of the fiber tips. The amplifier is set up in the bi-directionally pumped configuration as seen in the Figure 3.8. M1 and M2 are dichroic mirrors reflective at the laser wavelength and transmissive at the pump wavelength. L1 and L2 are matched lenses used to launch pump light from the two 300W, 0.22NA 400 micron core LIMO diodes used to pump the amplifier. Launch efficiency of the pump light from the 300W diodes is ~75%, so approximately 450W of pump light is available to pump the amplifier. The fiber is mounted on a water cooled 11cm diameter mandrill to both manage temperature and control beam quality. The passive fiber sections are held in water cooled grooves to be sure they are appropriately cooled. Thermal management is crucial in this system as improper management leads to inefficient laser operation and potential catastrophic damage to the fiber. In order to achieve the >15 minute operation stability the pump launch optics are also water cooled, as they are not ideally coated for the pump wavelength and hence can heat up over time.

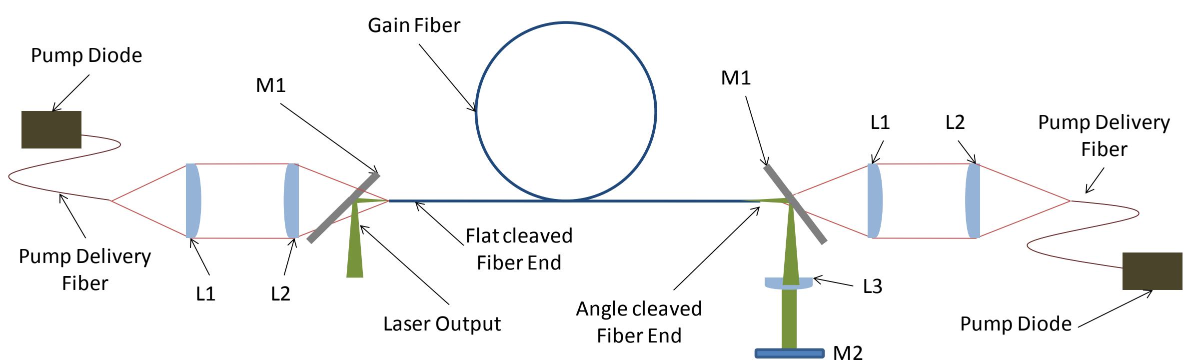


Figure 3.8. Schematic of the 200W dual-end pumped Tm fiber laser.

The current state of the system involves testing for stability over time. To eliminate the variable of the seed laser (and potential damage from mis-launching of its beam), the power amplifier was turned into an oscillator by simply adding a mirror onto one end of the fiber M3. Doing so allowed easier high power testing at the expense of loss of wavelength control. Upon solving thermal management issues discussed earlier the system was optimized for operation at the 200W power level and was operated there for an extended period of time (10W drift in 10 minutes). The drift is currently believed to be related to damage that occurs on the output mirrors of the laser. This damage occurs due to water absorption in the coating gradually damaging the coating over the time of the test. Figure 3.9 shows a slope efficiency curve for the laser oscillator. Efficiency is nearly 60% even at the high power levels with respect to launched pump power. This slope efficiency should be compared to the ~39% quantum defect of thulium. It is clear that there is significant cross relaxation occurring to enhance the laser efficiency, as is expected advantage of the thulium ion. The actual slope efficiency is even higher, as the numbers presented are quoted with regard to launched pump power rather than absorbed pump power. There is only approximately <95% absorption of the pump power due to fiber length constraints. The slight roll off at the high end of the plot is likely due to a combination of the beginnings of damage to the output mirror as discussed before and wavelength drift of the pump diodes. As their power is increased, their center wavelength drifts off of the peak of the thulium absorption band. The diodes are already being run at 10 Celsius temperature, so cooling them further to achieve better wavelength overlap at high power needs extra care to avoid condensation. The beam quality of the laser was found to be extremely high when measured on commercial beam quality measurement equipment. Power levels up to 50 W were directly measured and M^2 was found to better than 1.3 and in some cases as good as 1.1. The beam quality is important for this particular system as it will be projected long distances into the atmosphere and thus the beam divergence must be kept very low. The 200 W level was achieved at a level below the full potential pump power, and as such there is likely room for increased output power to the ~250W range with thermal and optical improvements to the system.

The next step in the task involves upgrading the master oscillator to allow for efficient seed launch into the power amplifier. The reasons for this are two-fold, both for efficiency of the laser and to avoid catastrophic damage to the power amplifier fiber which could be caused by "hot spots" related to modal interference caused by improperly launched seed light. With these improvements complete the MOPA can be seeded and 200W tests can continue. It is expected that the laser slope efficiency will be maintained at ~60% levels demonstrated in the master oscillator. Additional work to fix the damage issue with the mirrors is also underway in order to allow for stable and reliable long term operation of the system so that it can be used for the future atmospheric and other tests.

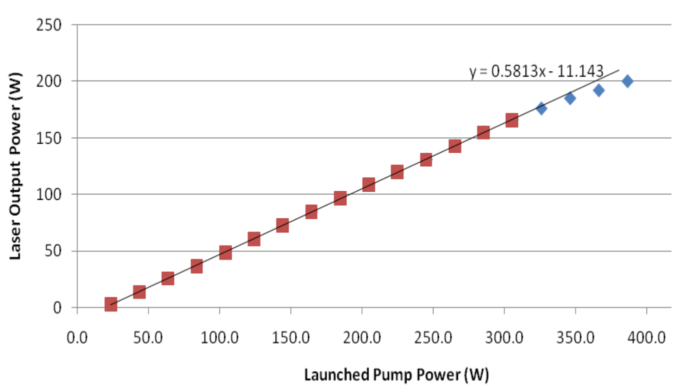


Figure 3.9. Output power versus incident total pump power.

Tunable and narrow line Tm fiber laser

Recent developments in fiber lasers are creating considerable interest because of their ability to generate very high average powers with excellent beam quality, minimal thermal management and high stability in terms of output power and beam quality. Ytterbium-doped large mode area (LMA) fiber lasers operating around 1 μm are able to achieve CW output powers in excess of 2 kW with single transverse mode operation. However, many current applications call for high power lasers operating in the eye-safe (wavelength > 1.4 μm) regime. The rare earth trivalent thulium (Tm) ion has received a great deal of attention as one of the candidates for many applications in the eye-safe spectral region including remote sensing, medical and defense applications as well as for its use as a pump laser for Holmium based systems and for conversion to high powers in the 3 - 5 μm mid IR range by nonlinear difference frequency processes. Thulium has the added advantage of possessing a cross-relaxation process that allows it to operate well beyond its quantum defect slope efficiency with very high output powers if the proper attention is paid to dopant concentration and thermal management.

Many current and forthcoming applications call for not only efficient high power operation, but also require stable, narrow linewidths. These narrow linewidths are required for such applications as hitting narrow atmospheric transmission windows around 2 μm for LIDAR and defense applications or for spectral beam combining where several high power narrow linewidth laser sources are combined using diffractive optical elements. In conventional fiber lasers fiber Bragg gratings (FBGs) can be used to provide stable, narrow linewidth, high reflectivity cavity mirrors with no need for alignment. However, LMA fiber technologies including photonic crystal fibers, and potential new chirally coupled core fibers and ultra large mode area (ULMA) gain guiding index antiguiding fibers capable of producing extremely large core sizes are yet to be completely compatible with current FBG technologies. Also, with some of these fibers achieving core sizes up to 400 μm it may be difficult to launch only the fundamental mode in an undoped FBG made to match mode field diameters. Thus, alternative methods to spectrally narrow these lasers must be sought.

The volume Bragg grating (VBG) is a potential solution for wavelength stabilization of these ultra large mode area fibers. VBGs are holographically produced 3D bulk gratings and are being increasingly used for wavelength stabilizing and spectrally narrowing solid-state and semiconductor laser diodes. Recently a VBG stabilized Neodymium doped photonic crystal fiber laser was reported. Under this program we report for the first time the use of a VBG to stabilize and spectrally narrow the broad spectral output of a 2 μm Tm doped LMA fiber laser. The characterization of this laser includes comparing results with those of a laser using a high reflectivity mirror in place of the VBG.

The fiber used for this experiment (project partner, Nufern) was fabricated from silica, and had a 400 μm flat-to-flat, 0.46 NA octagonal shaped cladding and a 25 μm diameter, 0.08 NA circular core. The length of the doped region of the fiber (~4.0 wt% Tm^{3+}) was approximately 5 m with an approximately 2 m section of undoped NA and core size matched fiber on each end to help reduce thermal stress on the directly end pumped fiber. The 5 m gain region of the fiber was wrapped around a water cooled 11 cm diameter aluminum heat sink to provide thermal management and hence improve laser efficiency, since the cross-relaxation process in Tm^{3+} is highly temperature dependent. The pumped end of the fiber was held in a water cooled copper clamp. Both fiber ends were hand polished at normal incidence with 0.3 μm polishing film, no angle polishing was required to allow stable VBG locking.

Made from photo-thermal-refractive glass, the 5 mm square aperture, 6.3 mm long VBG [OptiGrate, Inc.] used for this experiment was formed via a holographic process [10]. The surfaces were not AR coated and the grating was tilted 0.6 degrees in the vertical and horizontal planes relative to the bulk end face to inhibit Fresnel reflections from interfering with the VBG reflectivity. The grating had reflectivity of greater than 95% and was designed with a line center of 2051.5 nm and a spectral FWHM of 0.55 nm.

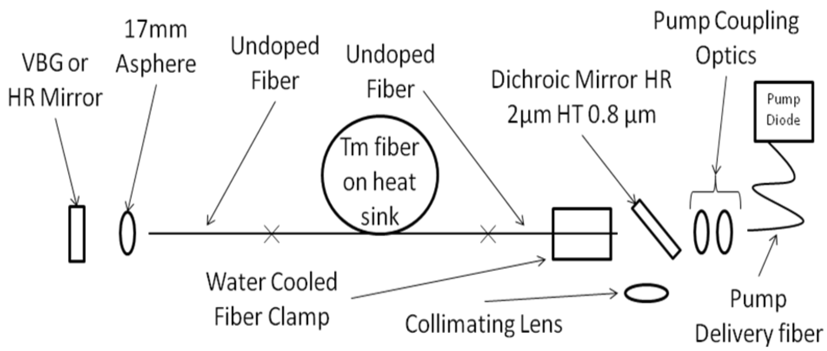


Figure 3.10. Schematic of the laser setup.

The laser resonator was formed on one side by the Fresnel reflection from the hand-polished end of the fiber and on the other side by a 17 mm focal length, uncoated aspheric lens made of B270 glass followed by either the VBG or a high reflectivity (HR, >99.5%) broadband dielectric mirror centered at ~2 μm. Light from a 795 nm Spectra Physics 40 W 0.22NA, 400 μm core fiber-coupled diode bar was launched through a dichroic dielectric mirror designed to be HR at ~ 2 μm and highly transmissive at ~ 795 nm at a mirror angle of 45° and into the fiber by way of two sets of infinite conjugate ratio fast achromatic doublet pairs with an NA of 0.26 and a working distance of 84 mm. Coupling efficiency for this scheme is ~60%, as estimated by launching into a short section of undoped fiber. This low efficiency is due to aberrations in the focused beam caused by focusing through the ~6.4 mm thick angled mirror as well as by losses in the uncoated pump focusing lenses. Figure 3.10 is a schematic of the laser cavity used in this experiment. Laser emission from the fiber was collimated by a 50 mm focal length NIR achromatic doublet and laser output power was measured with a Coherent PM-10 thermal power meter.

The output power characteristics of the two lasers are shown in Figure 3.11. The laser with the HR mirror produced a maximum output power of 6.2 W with a slope efficiency of 44% with respect to absorbed pump power and an absorbed pump power threshold of 8.6 W. The VBG laser performed very similarly with a maximum output power of 5.6 W, a slope efficiency of 41% with respect to absorbed pump power and an absorbed pump power threshold of 8.9 W. It should be noted that the overall efficiency in both cases is adversely affected by the lens used to collimate before the high reflection end of the cavity. This lens had no antireflection coating and the lens glass had some absorption at the 2 μm laser wavelength. Preliminary measurement revealed the lens to be 15% lossy at 2μm. The effect of this loss is clearly observed on laser performance, as when the lens was left out and the HR mirror was butted to the end of the fiber, the slope efficiency of the laser increased to greater than 50%. It should also be noted that the 50 mm focal length achromatic doublet used to collimate the laser output before the power meter was AR coated, but had 15% loss due to absorption in the glass and optical cement between lenses. The reported output power results are corrected for this loss.

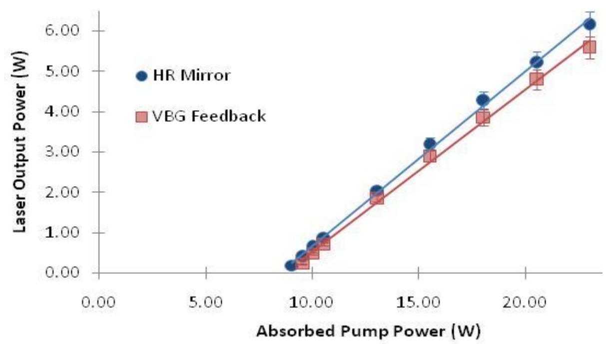


Figure 3.11. Output power versus absorbed pump power for HR and VNG lasers. Note the error bars denote 5% error associated with fluctuations in the power meter readout.

Spectral characteristics of the laser were analyzed using a McPherson 218 scanning monochromator containing a 300 line/mm grating blazed at 2 μm. The resolution of the monochromator is estimated to be ~ 0.3 nm. The detector used, a 0.5 mm diameter InGaAsSb photodiode with built in TEC, had a broadband sensitivity from 0.8 - 2.4 μm. The spectrum of the HR mirror laser showed a number of significant lines lasing simultaneously over a total bandwidth of 12 nm, centered around 2027 nm. This wavelength was observed to be highly dependent on the gain in the fiber laser, when no HR mirror is used and the laser was operated with only ~ 4% Fresnel reflection feedback on both ends the center wavelength shifts down towards 2007 nm and the number of lines lasing decreases. The harder the laser is pumped, the broader the laser spectrum becomes. When the VBG is used as an end mirror, the laser line center jumps to 2053.9 nm according to the monochromator and the linewidth drops to approximately 300 pm, which is likely limited only by the resolution of the spectrometer. It should be noted that the line center measured by the monochromator is different from the line center specified by OptiGrate by ~3 nm. This discrepancy is most likely due to poor calibration of the scanning monochromator. The VBG stabilized spectrum showed no sign of jitter and the laser stayed locked to the line even as pump power levels were increased. There were no signs of other parasitic lasing from the cavity formed by the two perpendicularly polished fiber ends, even at the maximum available pump power, this is because the feedback from the VBG is much stronger than the Fresnel reflections for the fiber facets, and hence the VBG feedback forces the laser to oscillate in that spectral regime only. It should be noted that the VBG was able to force the laser to operate quite far from the peak of the gain defined by where the laser operated with the HR mirror. Figure 3.12a is a comparison of the spectra of the HR and VBG lasers and Fig. 3.12b is the VBG laser spectrum itself.

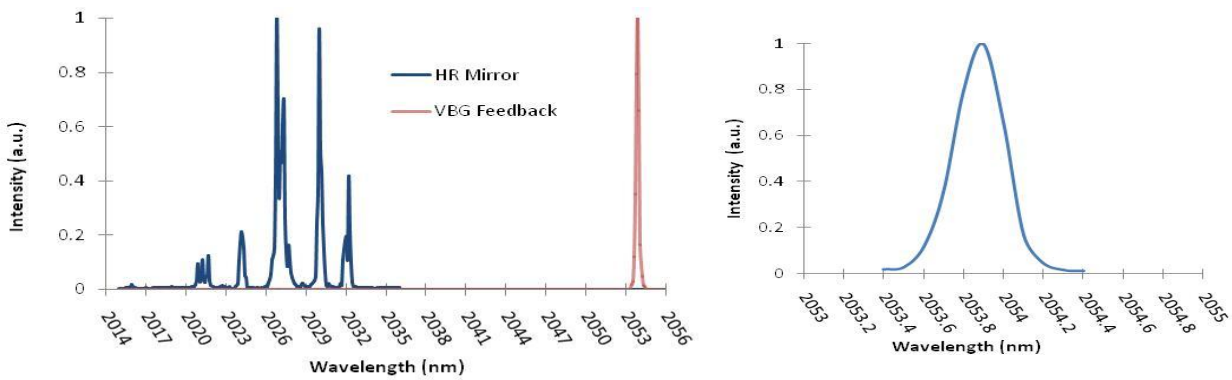


Figure 3.12. (a) HR and VBG laser output spectra at maximum absorbed pump power of approximately 23W and (b) VBG laser spectrum at pump power of approximately 23W.

A Spiricon Pyrocam III was used to image the output beam, and to measure its divergence using the well known technique of scanning along the beam as it is focused through greater than the Rayleigh range of a 1 meter focal length lens. Such a long focal length lens was used to ensure that the beam waist was large enough to be accurately detected on the relatively low resolution Spiricon (85 x 85 μm pixel size). The value of M^2 was ~1.4. This relatively high beam quality is expected because although the V parameter of this fiber was approximately 3.06, the 11 cm coiling diameter was sufficient to strip off any higher order modes from the low NA core. It is expected that the beam quality would improve if the fiber ends were cleaved rather than hand polished, which introduces some beam distortion.

The laser performance of the resonator using the VBG is nearly identical to that of the resonator using the HR mirror, showing that a VBG is an ideal optical element for use in narrowing the spectrum of large mode area fiber lasers when conventional fiber Bragg technology is impractical or impossible to use. This maintenance of efficiency performance at narrow linewidth is expected due to the fact that the Stark splitting of the Tm $^3F_4$ levels due to the local crystal field is comparable to the energy level difference arising from the site-to-site variations in the amorphous silica glass host, resulting in the gain medium acting homogeneously broadened. The slightly lower slope efficiency of the laser with the VBG compared to that of the laser constructed with the HR mirror can be explained by the combined lack of an antireflection coating on the VBG and its 95% reflectivity, thus adding ~9% loss to the laser resonator, raising the laser threshold and imposing an adverse effect on efficiency. A VBG with higher reflectivity and AR coatings would bring the slope efficiency up to a value closer to that of the HR mirror cavity, and a further improvement on overall efficiency in both cases would be made by reducing overall cavity losses by using an AR coated lens with minimal aberrations and low absorption at the laser wavelength as well as using cleaved, rather than hand polished fiber ends. The fiber length used for this experiment was long for the relatively low pump powers used. As a consequence, the laser threshold was higher than for an optimized fiber length. Future work will involve pumping with much higher diode power to improve laser output power.

A VBG has been used for the first time to spectrally narrow a Tm fiber laser, producing a 5 W output power with a linewidth of < 300 pm centered at 2053.9 nm, limited by the resolution of the spectrometer. The laser slope efficiency and spectrum were compared to a laser resonator formed by a high reflectivity mirror. The VBG completely stabilized the laser, narrowing the spectral width from more than 10 nm to less than 300 pm. VBG stabilization will be most highly applicable to thulium lasers with large core sizes that are difficult or impossible spectrally narrow utilizing existing FBG technologies, thus enabling high peak powers with narrow linewidths from compact fiber laser sources.

Locked narrow line operation with GMRF

Theory of Guided Mode Resonance Filters (GMRFs) stems from discoveries R. W. Wood made in 1902 concerning variations in the intensity of the diffracted spectral orders over a narrow frequency range. Wood discovered two separate anomalies, the first described by Lord Rayleigh in 1907 concerns the variation of intensity of diffracted orders when orders appear or disappear. The second theory describing the resonance anomaly seen by Wood was described by Hessel in 1965. GMR occurs when a diffraction grating couples the diffracted orders into guided modes in a waveguide structure, but a resonance feature is created when the guided mode leaks back onto the incident wave because of index modulation of the waveguide. GMR filters have shown promise as feedback as stable narrow linewidth feedback elements for fiber lasers due to the ability to tailor diffraction gratings to narrow the linewidth.

GMRFs have been used as feedback elements to stabilize and narrow the linewidth of erbium-ytterbium fiber and produced lasing at 1540.8 nm with a linewidth of 0.18 nm. To produce GMR filter as an external feedback elements for Tm^{3+} a 486 nm SiN waveguide region was deposited onto a fused silica substrate while a 100 nm SiO2 grating layer was deposited onto the SiN layer. Diffraction gratings were produced in a hexagonal hole array pattern with different hole sizes to vary wavelength and resonance properties. Filters were designed to operate at 2 μm while the spectral reflectivity of grating has a FWHM value of 0.4 nm.

Guided Mode Resonance filters (GMRFs) designed to operate near 2 μm were inserted as a stable narrow linewidth feedback element in a laser cavity comprised of a 4-m Tm fiber with a 40W pump diode operating at 790 nm. A 400 μm delivery fiber coupled light through two fast acromat lenses, which collimated and focused the pump light into the 400/25 μm active fiber. GMRFs were placed as the feedback element and slope efficiencies, laser wavelength, laser linewidth, and spectral reflectivities were measured for 67 different filters. Measurements for resonance wavelengths and spectral reflectivities were measured using a McMcPherson monochrometer with a 300 line/mm grating and laser linewidth was measured using a Fabry Perot interferometer. Resonance wavelength output varied from 1975 to 1989 nm with an average value of 1983 nm while linewidth were measured below two times the laser threshold yielded results <30 pm. Filters were designed to have a 0.4 nm spectral reflection linewidth and were measured to be between 0.45 and 1 nm while peak reflectivity from the filters averaged 25%.

Shown in Figure 3.13 is a typical output power versus total incident pump power whereas Figure 3.14 shows a typical spectral reflectivity of a filter with its linewidth.

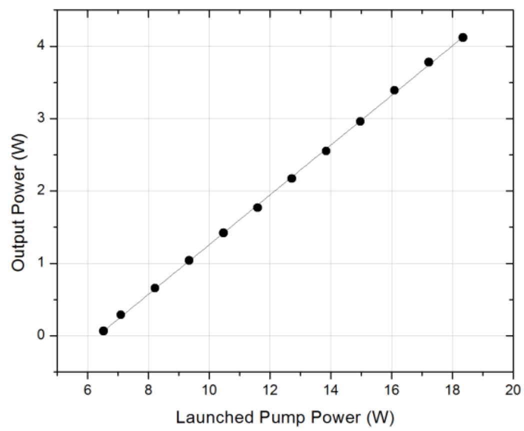


Figure 3.13. Filter exhibiting 31% slope efficiency with respect to launched pump power.

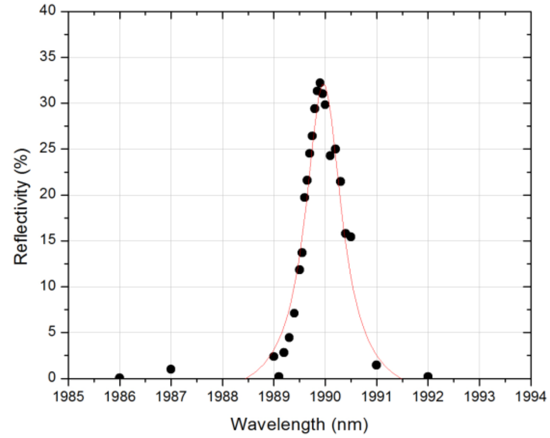
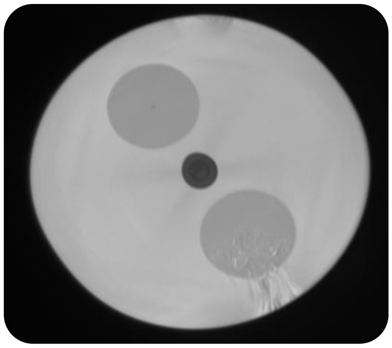


Figure 3.14. Spectral reflectivity of Filter with 0.85 nm linewidth.

Tm doped Photonic Crystal Fiber (PCF) lasers

Comparison of Q-switching performance and high-order mode suppression between step-index and PCF large mode area fibers

Following on the program's development of thulium-doped fiber lasers using PCF (fabricated by NKT Photonics) and step-index LMA fiber (fabricated by Nufern), see Figure. 4.1, we have recently explored and compared the modal properties of both fibers.



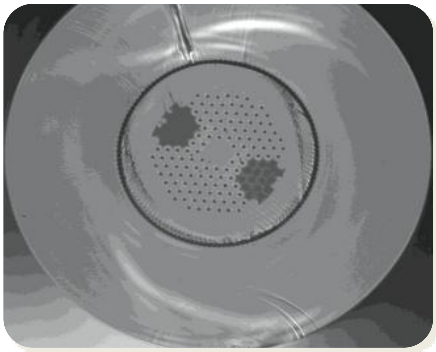


Figure 4.1: Cross-sections of the thulium-doped fibers tested, left) 25/400 PM step-index fiber from Nufern; right) 50/250 polarizing PCF from NKT Photonics

Based upon the large MFD, it is expected that the Tm:PCFs would generate significantly higher peak-powers than possible in solid-core step-index fibers. However, we have found that the Tm:PCFs tend to have significantly higher laser thresholds and do not provided high efficiency through 2:1 pump cross-relaxation.

In order to compare the performance of both fibers as pulsed laser sources, we constructed a Q-switched oscillator in which the active fiber was inter-changeable. The cavity configuration is shown in Figure 4.2. In particular, we compare the powers measured directly after the pump rejection filter, P_{total}, and the power measured after transmission through a polarizer and an aperture, P_{use}. By filtering out an unpolarized or cladding light, we compare the utility of both laser configurations. Figure 4.3 shows that the percentage of usable power degrades significantly as pulse energy increases for the LMA fiber, whereas there is no such degradation for the PCF.

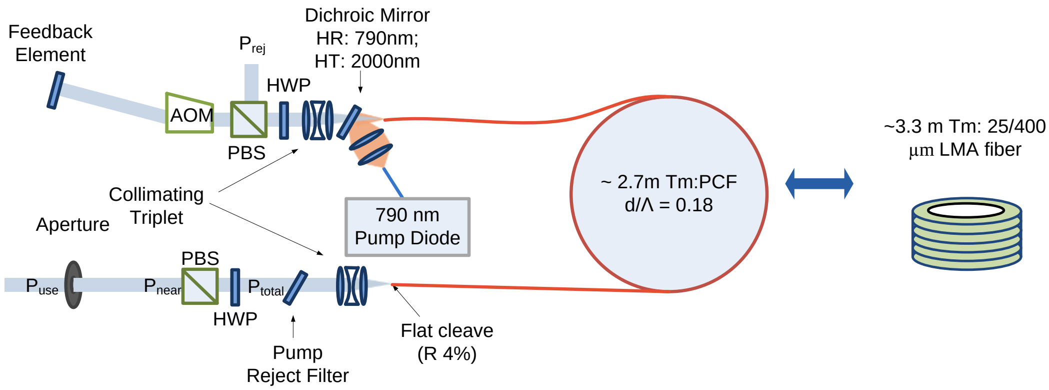


Figure 4.2. : Q-switched laser oscillator schematic. The two fiber types Tm: PCF and Tm: LMA were exchanged while keeping all other components the same for comparative testing. (AOM: Acousto-optic modulator, HWP: Half wave plate, PBS: Polarizing beam splitter).

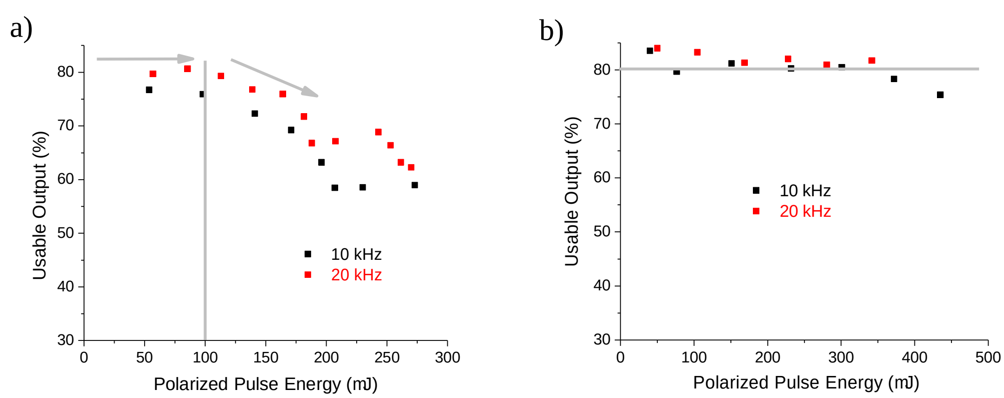


Figure 4.3: The usable output in the core as a percentage of total power (core + cladding) with respect to pulse energy obtained for a) LMA fiber and b) PCF at 10, 20 and 50 kHz repetition rates.

As part of this work, we have collaborated with Prof. Schülzgen's research group (UCF) to characterize the S^2 of passive versions of both fibers. The results summarized in Figure 4.4, show that the LMA fiber supports much a greater amount of power in higher order modes than the PCF.

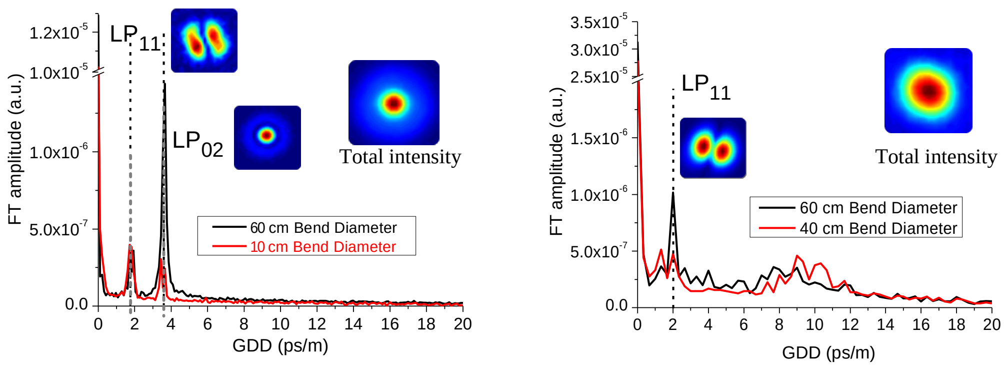


Figure 4.4: S^2 data: a) PM-LMA fiber, and b) PCF

Nanosecond pulse amplification in PCF

Although the Q-switched oscillator performance of the PCF exceeded that of the step-index LMA fiber, it did not reach the limits of energy handling or nonlinearity. In order to achieve higher pulse energy and lower pulse duration, we are now investigating the PCF as a nanosecond pulse master amplifier using the configuration shown in Figure 4.5. The output performance is summarized in Figure 4.6.

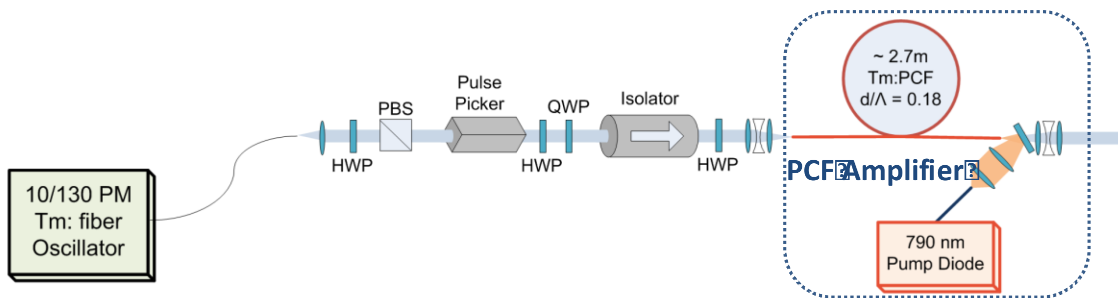


Figure 4.5: Master oscillator power amplifier schematic

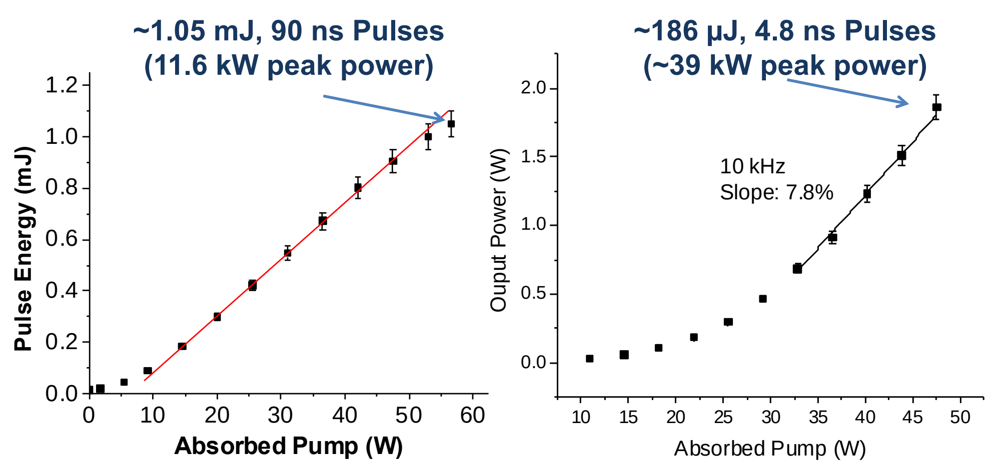


Figure 4.6: Output pulse energy as a function of pump power at 10 kHz repetition rate, (left) Amplifier performance at maximum pulse energy, 1.05 mJ with 90 ns pulse duration; (right) Amplifier performance at maximum peak power, 39 kW with 4.8 ns pulse duration

Report Type: Annual Progress Report
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Summary of Scholarly Productivity

<u>*Papers published peer-reviewed*</u>

1. A. E. Siegman, Y. Chen, V. Sudesh, M. Richardson, M. Bass, and J. Ballato, " Confined Propagation and Near Single Mode Laser Oscillation in a Gain Guided, Index Anti-Guided Optical Fiber," *Applied Physics Letters* 89, article 251101 (2006).
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3. A. E. Siegman, "Gain-guided, index-antiguided fiber lasers," *Journal of the Optical Society of America B*, Vol. 24, 1677-1682 (2007); [**Special Issue on Fiber Lasers**].
4. Y. Chen, V. Sudesh, M. C. Richardson, M. Bass, J. Ballato, and A. E. Siegman, "Experimental demonstration of gain guided lasing in an index anti-guiding large mode area fiber," in *Advanced Solid-State Photonics 2007 Technical Digest* (OSA; ISBN: 1-55752-829-2).
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13. G. Frith, A. Carter, B. Samson and G. Town, "Design considerations for short-wavelength operation of 790nm-pumped Tm-doped fibers", Applied Optics **48**, 5072 - 5075 (2009).
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Presentations

1. A. E. Siegman, Y. Chen, V. Sudesh, M. Richardson, M. Bass, and J. Ballato, "Large area, near single mode oscillation in gain guided, index anti-guided fibers," Optical Society of America annual meeting October 2006.
2. G. Frith, J. Farroni, A. Carter, B.Samson, K. Tankala, "High efficiency 110W Monolithic FBG tuned 2 μm fiber laser," *CLEO Europe*, Munich, (2007).
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11. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Optics Research Center, University of Southampton, Southampton, UK, June 2007. **INVITED**
12. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Integrated Optical Micro Systems (IOMS) Group, Department of Electrical Engineering, University of Twente, Enschede, The Netherlands, June 2007. **INVITED**
13. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Institute for Optics, Information and Photonics, University of Erlangen-Nuremberg, Germany, June 2007. **INVITED**
14. A. Siegman, “Index Antiguided Optical Fibers and Fiber Lasers” seminar given at the Department of Physics, University of Hamburg, Hamburg, Germany, June 2007. **INVITED**
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16. McComb T., Sudesh V., Chen Y., Bass M., Richardson M., Ballato J., and Siegman A. E. “Single mode lasing in gain-guided index anti-guided diode end pumped fiber,” Paper no. CThL5, CLEO 2008
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21. T. McComb, R. Sims, M. Reichert, V. Sudesh, M. Richardson, M. Poutous, Z. Roth, and E. C. Johnson, “VBG and GMRF stabilized continuous wave, tunable (50 nm), narrow linewidth, thulium fiber laser,” Photonics West, San Jose, CA, January 2009.
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Books/Book Chapters

T. McComb, M. Richardson and M. Bass, “Progress in high power fiber lasers” Handbook of Optics, M. Bass, Ed., to be published (2009).

Honors

In addition to the aforementioned invited and plenary talks Principal Investigator John Ballato was elevated to the rank of Fellow of the American Ceramic Society (ACerS), the International Society of Optical Engineering (SPIE), and the Optical Society of America (OSA) during the duration of this program.

Patents

1. **US Patent 7,668,211**, “Waveguide-Pumping Gain Guided Index Anti-Guided Fiber Lasers,” V. Sudesh, T. McComb, M. Richardson, W. Hagemann, M. Bass, J. Ballato, and A. Siegman (2010).

2. “Gain-Guiding in Photonic Bandgap Fibers: A New Platform for Ultra High Power Lasers and Amplifiers,” inventor: Tsing-hua Her (UNCC).
3. “Hybrid gain guiding in laser resonators,” Inventors: T. McComb, M. Richardson, and V. Sudesh (UCF).

Technology Transfer

1. Using new pump diodes together with the components and high efficiency Tm-doped fibers developed under the MRI, an air cooled 50W 1940nm fiber laser product has been introduced by program partner, Nufern. Multiple shipments to OEM customers have been completed using technology developed under the MRI program.
2. High temperature fluoropolymers coatings have been developed and transitioned to commercial partner.

Faculty:

The following faculty were involved at the participating institutions:
Clemson University: Dr. John Ballato (Prof)
University of Central Florida: Dr. Martin Richardson (Prof), Dr. Michael Bass (Prof)
University of North Carolina at Charlotte: Dr. Tsing-hua Her (Assistant Prof)

Grad Students:

Clemson University: Stephen Budy, Scott Iacono
University of Central Florida: Timothy McComb, Michael Hemmer, Robert Sims, Pankaj Kadwani , William Hagermann, Christina C.C. Willis, Joshua D. Bradford, Clemence Jollivet, Faleh Altal
University of North Carolina at Charlotte: K. Fan, Mingzhen Tang

Post Doctorates:

University of Central Florida: Dr. Vikas Sudesh, Dr. Giorgio Turri

Master Degrees granted:

Viktor Diefenbach, University of Applied Science, Darmstadt 2006 (joint with UCF), Tim McComb (UCF), Christina Willis (UCF), and Michael Hemmer (UCF)

Under Graduates:

Clemson University: Nicholas Brabham, Dale Edmondson
University of Central Florida: Erik McKee, Cheree Armstrong, John Szilagyi, Erik McKee
University of North Carolina at Charlotte: Dylan Mosses

Doctorate Degrees granted:

Scott Iacono (Clemson), Tim McComb (UCF), William Hageman (UCF)

Other Staff

Clemson University: Paul Foy, Thomas Hawkins, Andrew James
University of Central Florida: Dr. Lawrence Shah and Ms. Y. Chen (Senior Scientist), Dr. Hyun Su Kim (Visiting Prof), Dr. Gyu Ug Kim (Visiting Prof), Dr. Lanlan Gao (Visiting Research Scientist), Mr. Xiangru Wang (Visiting Research Scientist)

New ARO Reporting Questions

(p) Number of undergraduates funded by your agreement during this reporting period: 7

(q) Number of undergraduates funded by your agreement who graduated during this period: 4

(r) Number of undergraduates funded by your agreement who graduated during this period with a degree in a science, mathematics, engineering, or technology field: 3

(s) Number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D degree in a science, mathematics, engineering, or technology field: 1

(t) Number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense: 0

(u) Number of undergraduates graduating during this period who achieved at least a 3.5 GPA based on a scale with a maximum of a 4.0 GPA: 2

(v) Number of undergraduates working on your agreement who graduated during this period and were funded by a DoD Center of Excellence for Education, Research, or Engineering: 0

(w) Number of undergraduates funded by your agreement who graduated during this period and will receive a scholarship or fellowship for further studies in a science, mathematics, engineering or technology field: 1